Performance and Evaluation of Various Radiation Based Models for Semi-arid Region

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A B S T R A C T

This study aimed to Performance of seven radiation models. The objective was to determine the most accurate model for estimating solar radiation. Performance and Evaluation of all the models on the same basis is prerequisite for selecting an alternative approach in accordance with available data such as air temperature (Tmax, Tmin, Tmean), actual sunshine hours (n), Relative Humidity (Rhmax, Rhmin & RHmean) and potential sunshine hours (N). Therefore, recommended Angstrom-Prescott (A-P) model locally calibrated A-P model, Dogniaux-Lemoine (D-L) model, Glower-Meculloch model, Hargreaves-Samani model (1985),Chen et al. (2004), Ertekin and Yaldiz (1999) and Almorox - Hontoria (2004) radiation based model were used to estimate monthly solar radiation (Rs) at Udaipur(Rajasthan), India. Further, the performance of all these methods were evaluated by regression and error analysis between standard Rs derived using FAO recommended Angstrom-Prescott (A-P) model and Rs values estimated using all the six models, on monthly basis. On monthly basis, Glower-Meculloch model performed best with highest coefficient of determination (1.00) and lowest Root mean square error (0.9089) MJ m^{-2} day^{-1}. Based on overall results it was concluded that the radiation based model provides average monthly accurate estimate of solar radiation compared to other models.

Introduction

Almost all of the energy that drives the various systems (climate systems, ecosystems, hydrologic systems, etc.) found on the Earth originates from the sun. Solar energy is created at the core of the sun when hydrogen atoms are fused into helium by nuclear fusion. The core occupies an area from the sun's centre to about a quarter of the star's radius. At the core, gravity pulls all of the mass of the sun inward and creates intense pressure. This pressure is high enough to force the fusion of atomic masses. For each second of the solar nuclear fusion process, 700 million tons of hydrogen is converted into the heavier atom helium. Since its formation 4.5 billion years ago, the sun has used up about half of the hydrogen found in its core. The solar nuclear process also creates immense heat that causes atoms to discharge photons. Temperatures at the core are about 15 million degrees Kelvin (27 million degrees F). Each photon that is created travels about

one micrometer before being absorbed by an adjacent gas molecule. This absorption then causes the heating of the neigh boring atom and it re-emits another photon that again travels a short distance before being absorbed by another atom. This process then repeats itself many times over before the photon can finally be emitted to outer space at the sun's surface. The last 20% of the journey to the surface the energy is transported more by convection than by radiation. It takes a photon approximately 100,000 years or about 1025 absorptions and re-emissions to make the journey from the core to the sun's surface. The trip from the sun's surface to the Earth takes about 8 minutes.

The irradiative surface of the sun, or photosphere, has an average temperature of about 5,800 Kelvin. Most of the electromagnetic emitted from the sun's surface lies in the visible band cantered at 500 nm (1 nm = 10-9meters), although the sun also emits significant energy in the ultraviolet and infrared bands, and small amounts of energy in the radio, microwave, X-ray and gamma ray bands. The total quantity of energy emitted from the sun's surface is approximately 63,000,000 Watts per square meter (W/m2 or Wm-2). The energy emitted by the sun passes through space until it is intercepted by planets, other celestial objects, or interstellar gas and dust. The intensity of solar radiation striking these objects is determined by a physical law known as the Inverse Square Law. This law merely states that the intensity of the radiation emitted from the sun varies with the squared distance from the source. As a result of this law, if the intensity of radiation at a given distance is one unit, at twice the distance the intensity will become only one-quarter. At three times the distance, the intensity will become only one- ninth of its original intensity at a distance of one unit, and so on.

Solar radiation

Solar radiation is radiant energy emitted by the sun, particularly electromagnetic energy. About half of the radiation is in the visible short-wave part of the electromagnetic spectrum. The other half is mostly in the near-infrared part, with some in the ultraviolet part of the spectrum. The amount of energy radiated by the sun and the average Earth-sun distance of 149.5 million kilometres, the amount of radiation intercepted by the outer limits of the atmosphere can be calculated to be around 1,367 W/m2. Only about 40% of the solar energy intercepted at the top of Earth's atmosphere passes through to the surface. The atmosphere reflects and scatters some of the received visible radiation. Gamma rays, X-rays, and ultraviolet radiation less than 200 nanometres in wavelength are selectively absorbed in the atmosphere by oxygen and nitrogen and turned into heat energy. Most of the solar ultraviolet radiation with a range of wavelengths from 200 to 300 nm is absorbed by the concentration of ozone (O_3) gas found in the stratosphere. Infrared solar radiation with wavelengths greater than 700 nm is partially absorbed by carbon dioxide, ozone, and water present in the atmosphere in liquid and vapour forms. Roughly 30% of the sun's visible radiation (wavelengths from 400 nm to 700 nm) is reflected back to space by the atmosphere or the Earth's surface. The reflectivity of the Earth or and body is referred to as its albedo, defined as the ratio of light reflected to the light received from a source, expressed as a number between zero (total absorption) and one (total reflectance).

Knowledge of the local global solar radiation is required by most models that simulate crop growth, and is also essential for many applications, including evapotranspiration estimates, architectural design, and solar energy systems. Design of a solar energy

conversion system requires precise knowledge regarding the availability of global solar radiation at the location of interest. Since the global solar radiation reaching the earth's surface depends upon the local meteorological conditions, a study of solar radiation under local climatic conditions is Essential. Solar irradiance can be estimated using empirical models (Almorox, 2011).

Therefore, various methods have been explored by many researchers to estimate, with reasonable accuracy, the solar radiation from other available meteorological data. Parameters used as inputs in the relationships include astronomical factors (solar constant, world-sun distance, solar declination and hour angle); geographical factors (latitude, longitude and altitude); geometrical factors (surface azimuth, surface tilt angle, solar altitude, solar azimuth); physical factors (albedo, scattering of air molecules, water vapour content, scattering of dust and other atmospheric constituents); and meteorological factors (atmospheric pressure, cloudiness, temperature, sunshine duration, air temperature, soil temperature, relative humidity, evaporation, precipitation, number of rainy days, total perceptible water, etc).

Total daily solar radiation is considered as the most important parameter in the performance prediction of renewable energy systems, particularly in sizing photovoltaic (PV) power systems, agriculture and building design applications (Sabziparvar and Shetaee, 2007).

Solar radiation arriving on earth is the most fundamental renewable energy source in nature. a reasonably accurate knowledge of the availability of the solar resource at any place is required by solar engineers, architects, agriculturists, and hydrologists for many applications of solar energy such as solar furnaces, concentrating collectors, and interior illumination of buildings. In spite of

the importance of solar radiation measurements, this information is not readily available due to cost, maintenance, and calibration requirements of the measuring equipment (Bakirci, 2009).

A good knowledge of solar radiation is essential for many applications, including agricultural, ecological, hydrological and soil–vegetation–atmosphere transfer models (Liu *et al.,* 2009). Despite its significance, accurate long-term records of solar radiation are not widely available due to the cost of measuring equipment and its difficult maintenance and calibration (Hunt *et al.,* 1998).

Solar energy is the most abundant renewable and sustainable energy source on earth. Due to the nature of solar energy which is inexhaustible and ubiquitous, it can be utilized extensively as an appropriate option to supply the worldwide energy demand and diminish the existing environmental problems such as climate change. Thus, the growth of solar energy technology industry has been significant recently (Gani *et al.,* 2015).

Objectives

Keeping in view the relevance of precise calculation of solar radiation (Rs) values for monthly average, present study was taken up with following major objectives:

1) To determine monthly average solar radiation: and
2) To compare Rs values obtained from different model with standard model.

Materials and Methods

This chapter encompasses description of study area, collection and analysis of metrological data and comparison of solar radiation by using six different models with Angstrom-Prescott (A-P) method.

General description of the study area

The study was conducted at Maharana Pratap University of Agriculture and Technology, Udaipur (24°N latitude, 73°E longitude, and 582.17 m above m.s.l.) in Rajasthan state of India which lies in south slope of the Aravalli Range in Rajasthan. The area has a Sami-arid sub tropical climate with three distinct seasons namely, summer (March- June), monsoon (July- October) and winter season (November- February).

Data collection and analysis of metrological data

The study was undertaken to estimated solar radiation by using six different models and Angstrom-Prescott (A-P) method. The metrological data on daily basis for the period of seven year (1983-1989), consisting of air temperature (maximum and minimum); relative humidity (maximum and minimum); wind speed; duration of actual sunshine hours, were collected from meteorological observatory situated in the premises of Crop Research Centre of the Maharana Pratap University of Agriculture and Technology, Udaipur.

Estimation of solar radiation

Angstrom-Prescott (A-P) model

The A-P model was first proposed by Angstrom in 1924 and further modified by Prescott in 1940. The A-P formula was developed based on the linear relationship between monthly mean daily Rs and sunshine hours as follows:

$$R_s = \left[0.25 + 0.50\left(\frac{n}{N}\right)\right]R_a \quad \ldots (1)$$

Where, Rs is solar radiation (MJ m^{-2} day^{-1}), Ra is extraterrestrial solar radiation (MJ m^{-2} day^{-1}), n is actual sunshine hours (ha), and N is potential sunshine hours (hs), and a (0.25) and b (0.50) are the empirical A-P coefficients.

Glower-McCulloch model

Glower and McCulloch (1958) presented the model below to predict global RS which is valid for $\phi < 60o$:

$$R_s = \left[0.29\cos\Phi + 0.52\left(\frac{n}{N}\right)\right]R_a \quad \ldots (2)$$

Where, Rs is solar radiation (MJ m^{-2} day^{-1}), Ra is extraterrestrial solar radiation (MJ m^{-2} day^{-1}), n is actual sunshine hours (ha), and N is potential sunshine hours (hs).

Dogniaux-Lemoine model

Dogniaux and Lemoine (1983) suggested the following equation, which takes in to account the effect of latitude of the site (Φ) as an additional input

$$R_a = \left\{0.37022 + \left[0.00506\left(\frac{n}{N}\right) - 0.00313\right]\Phi + 0.32029\left(\frac{n}{N}\right)\right\}R_a \quad \ldots (3)$$

Where, Rs is solar radiation (MJ m^{-2} day^{-1}), Ra is extraterrestrial solar radiation (MJ m^{-2} day^{-1}), n is actual sunshine hours (ha), and N is potential sunshine hours (hs).

Hargreaves-Samani model

According to Hargreaves and Samani (1985), the difference between the maximum and minimum temperature is related to the degree of cloud cover in a given location. Clear-sky conditions result in high temperatures during the day (Tmax) because the atmosphere is transparent to the incoming RS and in low temperatures during the night (Tmin) because less outgoing long wave radiation is absorbed by the atmosphere. On the other hand, in overcast conditions, Tmax is relatively smaller because a significant part of the

incoming RS never reaches the earth's surface and is absorbed and reflected by the clouds. Similarly, Tmin will be relatively higher as the cloud cover acts as a blanket and decreases the outgoing longwave radiation. Therefore, the differences between the maximum and minimum temperature (Tmax-Tmin) can be used as an indicator of the fraction of extraterrestrial radiation that reaches the earth's surface (Hargreaves and Samani 1985). The Hargreaves-Samani formula for estimating RS (MJm-2 day-1) is as follows:

$$R_s = K_{rs} \sqrt{(T_{max} - T_{min})} R_a \quad \text{……. (5)}$$

where Ra is the extraterrestrial radiation (MJm-2 day-1), Tmax is the maximum air temperature (°C), Tmin is the minimum air temperature (°C) and *RS K* is an adjustment factor which was initially set to 0.17 for arid and semi-arid regions.

Hargreaves (1994) later recommended values of 0.16 and 0.19 for inland and coastal regions, respectively. Daily Ra is given by the following equation (Allen *et al.,* 1998):

Chen *et al.,* (2004) proposed the following model:

$$R_a = [0.28 In(T_{max} - T_{min}) - 0.15] R_a \quad (6)$$

where Ra is the extraterrestrial radiation (MJm^{-2} day^{-1}), Tmax is the maximum air temperature (°C), Tmin is the minimum air temperature (°C)

Ertekin and Yaldiz

Ertekin and Yaldiz (1999) reported that RS can be calculated by the following Equation

$$R_s = -4.46 + 0.477R_a + 0.226\,T \quad \text{……(7)}$$

where Ra is the extraterrestrial radiation (MJm-2 day-1), Tmean is the mean air

temperature (°C).

Almorox-Hontoria model

Almorox and Hontoria (2004) have suggested an exponential type model as:

$$R_s = \left[-0.071 + 0.3096 exp\left(\frac{n}{N}\right) \right] R_a \quad \text{…..(8)}$$

Where, Rs is solar radiation (MJ m^{-2} day^{-1}), Ra is extraterrestrial solar radiation (MJ m^{-2} day^{-1}), n is actual sunshine hours (ha), and N is potential sunshine hours (hs),

Results and Discussion

The present study was carried out to determine solar radiation value for metrological observatory of Department of Soil and Water Engineering, College of Technology Agriculture engineering situated in Udaipur district of Rajasthan state by using value of Rs obtained with Angstrom-Prescott (A-P) model and various radiation based model to assess performance of various models for determining the Rs value.

Comparison of Rs value determined by various model with Angstrom-Prescott (A-P) method model on average monthly basis

The data related to comparison between Observed values and Estimated values Monthly average daily solar radiation (MJm^{-2} day^{-1}) for six Models are presented in Table 1.

Daily solar radiation by various equations was estimated and compared with observed radiation at the weather station. Figure 1 showed that the values of solar radiation for Dogniaux-Lemonine model were overestimated from Angstrom-Prescott (A-P) model for June, July and August by 1.39, 9.16 and 14.61 % respectively and underestimated for remaining months. The values of solar

radiation for Almonrox-Hontria (2004) model were underestimated from Angstrom-Prescott (A-P) model in all months. the Glower-Meculloch model were overestimated from Angstrom-Prescott (A-P) model for all 12 months by 4.61, 4.61, 4.66, 4.66, 4.67, 4.76, 4.92, 5.04, 4.72, 4.62 and 4.60% respectively. For Ertekin-Xaldiz (1999) model were overestimated with observed model in two month (July and August) by 10.92 and 25.32 and underestimated for remaining months. the value of solar radiation for Hargreaves-Samani model were overestimated with observed model in the six months (January, February, March, October, November and December) by 9.00, 4.01, 6.63, 7.34, 11.53 and 15.16 % respectively and underestimated in all months. the Chen *et al.,* (2004) model were overestimated from Angstrom-Prescott (A-P) model for January, February, march, October, November and December by 5.71 %, 1 %, 3.76%, 4%,7.31%, and 11.19% respectively and underestimated for remaining months.

Table.1 The comparison between observed values and estimated values monthly average daily solar radiation ($MJm^{-2} day^{-1}$) for six Models

MODEL	MONTHS											
	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Observes	15.5072	19.1096	21.3236	24.4313	25.6978	23.0783	18.6527	15.4949	19.3408	18.5381	16.0132	14.1019
Dogniaux-Lemonine	14.6085	17.9606	20.5257	23.5508	24.9440	23.4000	20.3627	17.7590	19.2264	17.4847	14.9593	13.3479
Almonrox-Hontria	13.0213	16.0814	17.4843	20.0004	20.9046	18.4614	14.8128	12.4836	15.5367	15.5520	13.5707	11.8003
Glower-Meculloch	16.2233	19.9913	22.3175	25.5707	26.8999	24.1786	19.5722	16.2763	20.2550	19.3947	16.7502	14.7618
Ertekin-Xaldiz	10.7612	13.5958	17.0328	20.1747	21.9487	21.7169	20.7004	19.4176	17.6685	14.4949	11.6891	10.0041
Hargreaves-Samani	16.9043	19.8761	22.7379	24.3345	23.5234	20.1447	16.0104	14.9601	18.0892	19.9164	17.8601	16.2406
Chen	16.3936	19.3020	22.1269	23.7686	23.1301	19.5687	14.5271	13.4661	17.6542	19.2811	17.1845	15.6805

Table.2 Statistical comparison between observed R_s values and those estimated by the six models

Models	R²	RMSE ($MJm^{-2} day^{-1}$)
Glower-Meculloch	1.000	0.9089
Almorox-Hontria	0.989	3.4656
Dogniaux	0.908	0.9799
H-G	0.763	1.5473
Chen	0.726	1.6624
Ertekin-Xaldiz	0.561	3.6663

Fig.1 Comparison between the Observed and estimated values by various models of solar radiation
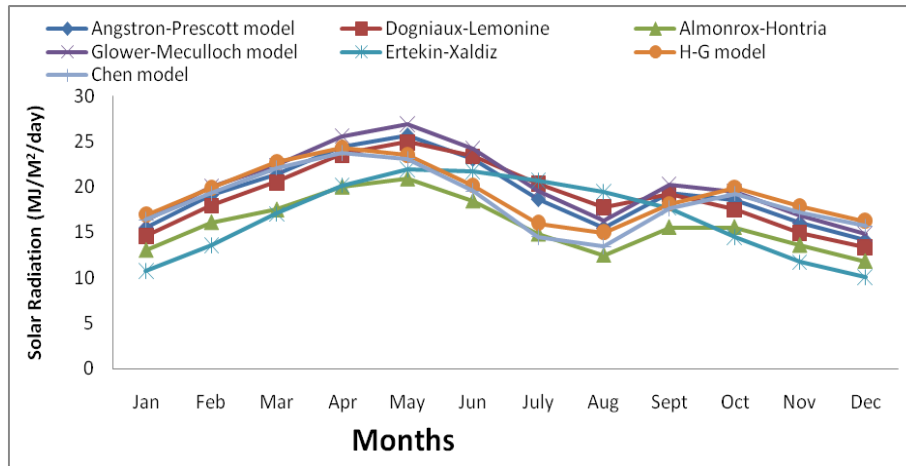

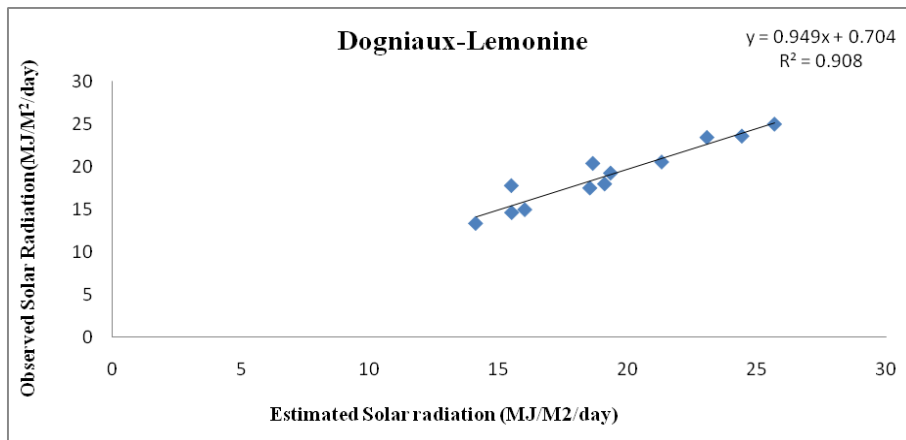**Fig.2** Estimated radiation from Dogniaux-Lemonine model against measured radiation

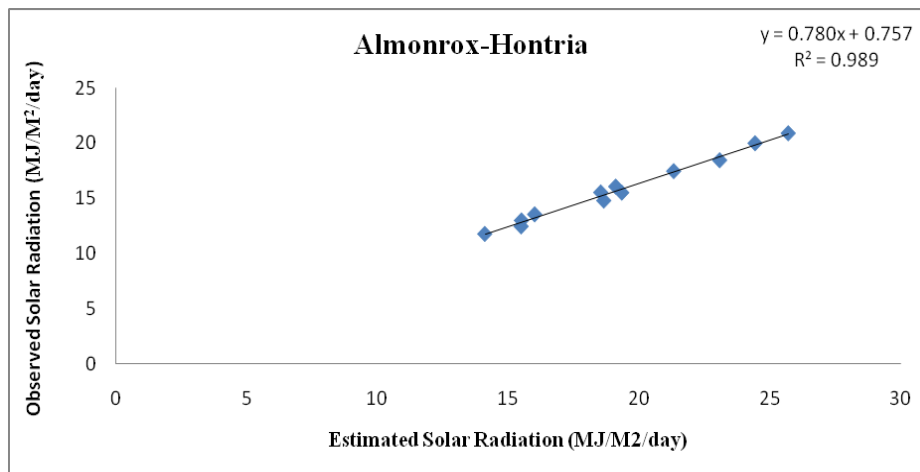**Fig.3** Estimated radiation from Almonrox-Hontria model against measured radiation

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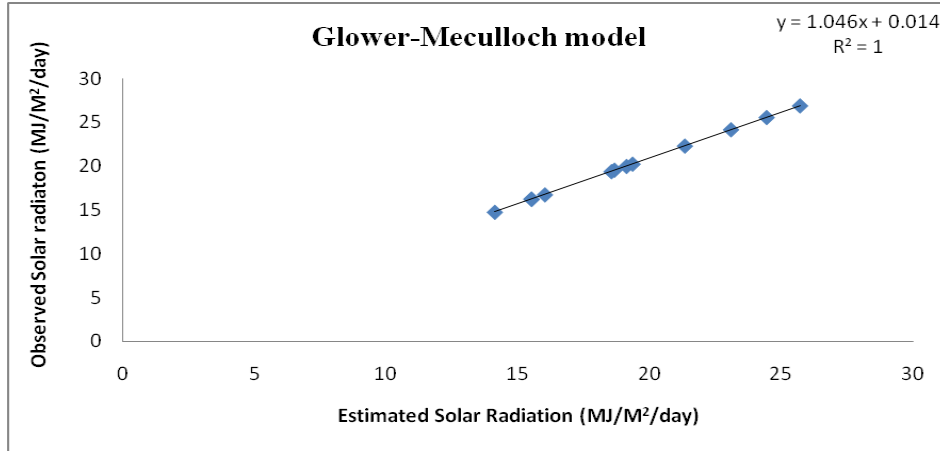**Fig.4** Estimated radiation from Glower-Meculloch model against measured radiation

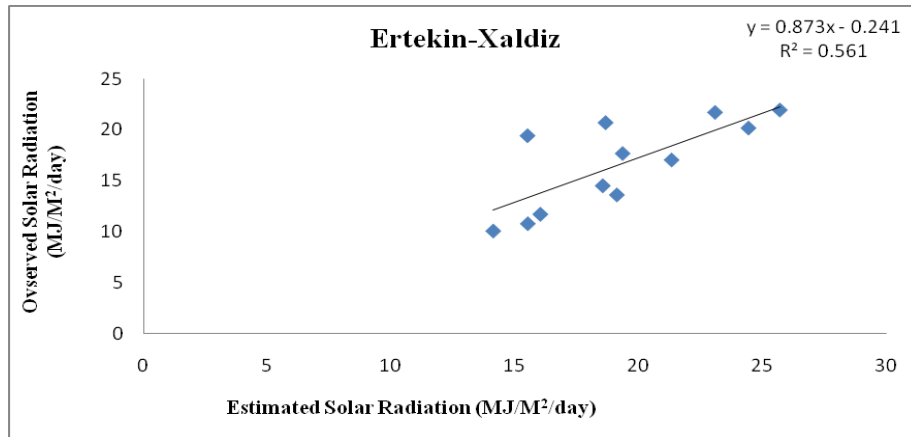**Fig.5** Estimated radiation from Ertekin- Xaldiz model against measured radiation

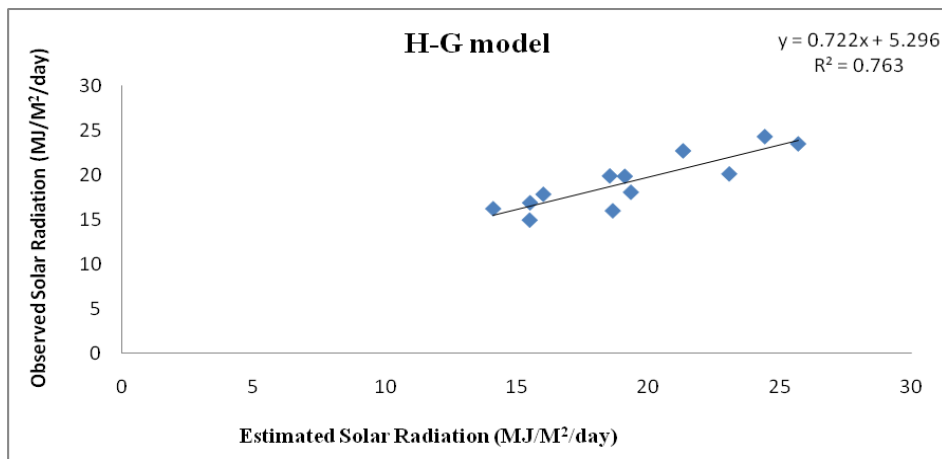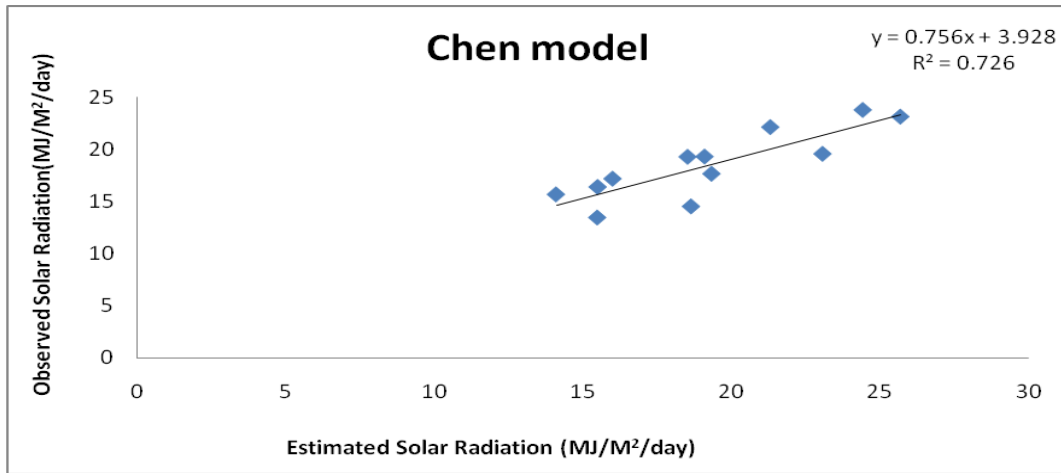**Fig.6** Estimated radiation from Chen model against measured radiation

Fig.7 Estimated radiation from Chen *et al.,* (2013) model against measured radiation

Statistics comparison

The statistical analyses for various radiation models are presented Table 2. A linear regression between the Rs values estimated by six models and the values observed in weather station is presented for Angstrom-Prescott (A-P) model. In each section of figure 2 to 6, the equation of regression line and coefficient of determination (R^2) are represented. Characteristics of regression line and the amounts of statistical indices resulting from comparison are represented also in Table 2. Table 2 showed that the values of coefficient of determination and root mean square error for various model.

The highest R² values were found for Glower-Meculloch model with a value of 1 and lowest for Ertekin - Yaldiz (1999) model with a value of 0.561. Similarly the highest RMSE value was found for Almonrox-Hontria (2004) model with a value of 3.4656 and lowest for Glower-Meculloch model with a value of 0.9089 (Fig. 7).

The result revealed that Glower-Meculloch model was more accurate method for calculating solar radiation.

Summary and conclusion are as follows

The main objective of this study was to determine value of solar radiation by various models as suggested by Hargreaves-Samani, Glower-Meculloch, Chen *et al.,* (2004), Ertekin and Yaldiz (1999), Almorox and Hontoria (2004), and Dogniaux-Lemonine in comparison to that observed by Angstrom-Prescott (A-P) model on the basis of long term daily meteorological dataset of 7 year (1983-1989) recorded at udaipur (24° 35' N latitude, 73° 42'E longitude, and 582.17 m above m.s.l.) in Rajasthan state of india. The other objective in this study includes, compareson analysis of monthly average of Rs values calculated by A-P model and various models.

The study was carried out at the Maharana Pratap University of Agriculture and Technology, Udaipur (Raj.) situated in southern region of Rajasthan region having a semi-arid sub tropical climate.

On monthly basis, average value of Rs determined by various model analysis varied from 26.8998 to 10.0409 with maximum value for the month of may and minimum for the month of December.

The good correlation was observed between Rs estimated by models proposed by Glower-Meculloch and Almorox-Hontoria (2004) Model.

The Glower-Meculloch model was more accurate method for calculating solar radiation compared to other various radiation based models.

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