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ORIGINAL ARTICLE

DEVELOPMENT OF NEW MODELS TO ESTIMATE GLOBAL SOLAR RADIATION IN NORTHWEST OF IRAN

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ABSTRACT: Solar radiation data are important for a wide range of applications in agronomy, ecology and hydrology as well as in the health sector and research in many fields of the natural sciences. However, lack of adequate measurements of global solar radiation has been a worldwide problem. Generating models for accurately estimating solar radiation from meteorological data is an important solution to the problem. In this paper, two well-known solar radiation models i.e. Angstrom-Prescott and Hargreaves were calibrated and ten new empirical global solar radiation models were developed. These models were calibrated based on available meteorological data and sunshine hours and validated using daily measured solar radiation data in 2001–2011 at Tabriz station. Most of the models presented in this paper showed an overall good result and some models provided even better results than the Angstrom-Prescott and Hargreaves models.
KEYWORDS: Meteorological variables, daily solar radiation, sunshine hours, model

INTRODUCTION

Solar energy is an important commodity furnishing the fundamental of every human activity for good life quality. This energy is the most ancient source and serves as root materials for almost all of fossil and renewable types of energy. Solar radiation is an inexhaustible source for future generations.

Solar radiation data at earth surface are important for a wide range of applications in the science of agronomy, ecology and hydrology, as well as in the health sector and in research in many fields of the natural sciences. Only some examples showing the diversity of applications include architecture and building design; solar heating system design and use; solar power generation; solar photovoltaic systems; weather and climate prediction models; evaporation and irrigation systems; determination of crop water requirements; monitoring crop growth and disease control and skin cancer research (Badescu, 2008).

In many applications of solar energy, the most important parameters that are often required are the daily short and long wave solar radiation. In spite of its importance, solar radiation is not widely measured compared to other meteorological data. For this reason, there have been attempts at estimating it from theoretical models. This correlations estimate the solar radiation values from readily available meteorological data such as actual sunshine hours, air temperature and relative humidity etc. Many empirical solar radiation models based on meteorological data have been discussed for estimation of global solar radiation (Francisco and Edvardo, 2000; Almorox and Hontoria, 2004; Mossad, 2004) among which the most widely used is the Angstrom-Prescott model (Prescott, 1940) and its revised model, which is based on sunshine duration. Hargreaves and Samani, (1982) reported a simple method to estimate global radiation which was a function of maximum and minimum air temperatures. Castellvi, (2001) developed a radiation equation based on precipitation and air temperature. Lewis, (1983) reported a solar radiation equation based on air relative humidity. *Chen et al.,* (2006) generated sixteen empirical global solar radiation models based on meteorological variables in china. From the comparison of reported results, models based on sunshine durations could give more accurate results than the models based on other meteorological variables without sunshine hours (Majnooni-Heris and Bahadori, 2014; Zand-Parsa *et al.,* 2011; Chen *et al.,* 2006; Can and Osman, 2000). Of course, the models based on sunshine durations and meteorological data could give more accurate results than the models just based on sunshine durations. The objective of this research is development and validation of several global solar radiation empirical models based on meteorological variables and sunshine durations data in the Northwest of Iran.

MATERIALS AND METHODS

The study place where the measurements have been performed (Tabriz Meteorological Station) is located 1364 m above sea level at a latitude

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and longitude of 38° 04′ 47″N, 46° 17′ 30″E, respectively. The global radiation and meteorological data reported in the paper are part of the data measured at the meteorological station of Tabriz from 2001 to 2011. Since the quality of some of the measured data was low, they were not selected for use in the generation of models.

Model constants were estimated by minimizing the sum of square errors from measured and predicted values. Performance of the models were evaluated by statistical error tests including coefficient of determination (R^2), root mean square error (RMSE), mean bias error (MBE) and the Nash-Sutcliffe equation (NSE) (Nash and Sutcliffe, 1970) as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}$$

$$\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)$$

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(O_i - P_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2}$$

Where, n is the total number of measurements, i is the measurement number, O and P are the measured and estimated values, respectively and $\bar{O}$ is the average of measured values. A model is more efficient when NSE is closer to one. The mean bias error value provides information on the long-term performance. A low MBE is desired. A positive value gives the average amount of over-estimation of an individual measurement, which will cancel under-estimation in separate measurements. The RMSE gives information on the short-term performance of the correlations by allowing a term-by-term comparison of the actual deviation between the predicted and measured data. The smaller the value, the better is the model's performance. However, a few large errors in the sum can produce a significant increase in the RMSE (Togrul *et al.*, 2000; Menges *et al.*, 2006).

RESULTS AND DISCUSSION

The Hargreaves and Samani, (1982) and original Angstrom-Prescott (Prescott, 1940) model were calibrated using the daily solar radiation data at study station. Then, some new equations based on available meteorological data and sunshine durations were developed and validated. The Hargreaves and Samani (Eq. 1) and Angstrom-Prescott (Eq. 2) model are the most commonly used methods given as follows:

$$Rs = a \times Ra \times \sqrt{(T_{max} - T_{min})} \quad (1)$$

$$Rs = Ra(a + b\frac{n}{N}) \quad (2)$$

Where, Rs and Ra are the global and extraterrestrial solar radiation, respectively, "a" and "b" are the coefficients of models and n, N, T_{max} and T_{min} are the actual sunshine hours, maximum possible sunshine hours, maximum daily air temperature and minimum daily air temperature, respectively.

Calibration of model 2 showed the values of "a", "b" and "a+b" coefficients are 0.2204, 0.5307 and 0.7511, respectively. These findings are in agreement with results of Allen *et al.*, (1998) and Liu *et al.*, (2009) in which they recommended "a+b" equal to 0.75 and 0.76, respectively. The value of model 1 coefficient ("a") calibrated equal to 0.1665 $C^{-0.5}$ for our study station. This amount is in agreement with finding of Allen *et al.*, (1998) in which they recommended it in the range of 0.16-0.19 $C^{-0.5}$. Statistical results showed the Angstrom-Prescott model accuracy is more than Hargreaves and Samani model after calibration.

There is a significant trend between some meteorological variables and global solar radiation. Relationship between the solar radiation and square root of the difference between the maximum and minimum air temperature is compared with square root of the difference between the maximum and minimum air relative humidity in Figure 1.

According to Figure 1, there is a clear trend between the radiation and square root of the maximum and minimum air temperature and relative humidity differences.

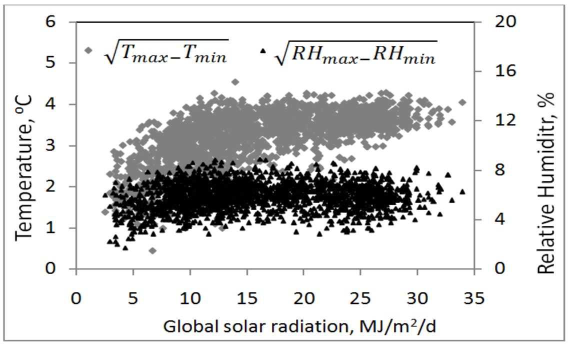

Figure1: Daily global solar radiation versus square root of the difference between the maximum and minimum air temperature and relative humidity.

Relationship between the daily global solar radiation, precipitation and saturated vapor pressure deficit are shown in Figure 2. Direct relationship was observed between global solar radiation and saturated vapor pressure deficit but it is indirectly related to rainfall.

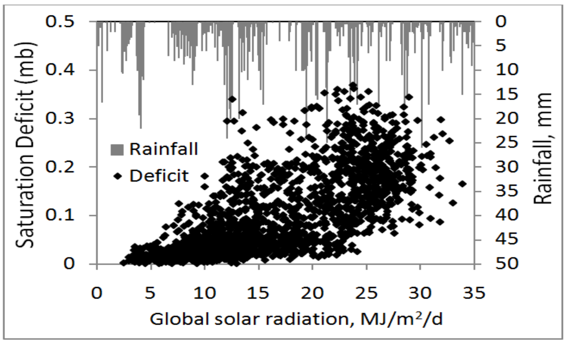

Figure 2: Daily global solar radiation versus precipitation and saturated vapor pressure deficit.

In this section, ten empirical global solar radiation models based on meteorological data and relative sunshine hours $\left(\frac{n}{N}\right)$ were generated and validated as follows:

$$Rs = Ra(a + b\sqrt{T_{max} - T_{min}} + c\frac{n}{N}) \quad (3)$$

$$Rs = Ra(a + bT_{mean} + c\frac{n}{N}) \quad (4)$$

$$Rs = Ra(a + bT_{mean} + c\sqrt{T_{max} - T_{min}} + d\frac{n}{N}) \quad (5)$$

$$Rs = Ra[\left(a + b\sqrt{T_{max} - T_{min}}\right) + \left(c + d\sqrt{T_{max} - T_{min}}\right)\frac{n}{N}] \quad (6)$$

$$Rs = Ra[(a + bT_{mean}) + (c + dT_{mean})\frac{n}{N}] \quad (7)$$

$$Rs = Ra(a + b\sqrt{T_{max} - T_{min}} + c\sqrt{RH_{max} - RH_{min}} + d\frac{n}{N}) \quad (8)$$

$$Rs = Ra[(aN + b\sqrt{T_{max} - T_{min}} + c) + dD + e] \quad (9)$$

$$Rs = Ra[\left(a + b\sqrt{T_{max} - T_{min}} + c\frac{n}{N}\right) + \left(d + e\sqrt{T_{max} - T_{min}} + f\frac{n}{N}\right)\frac{n}{N}] \quad (10)$$

$$Rs = Ra[\left(a + bT_{mean} + c\frac{n}{N}\right) + \left(d + eT_{mean} + f\frac{n}{N}\right)\frac{n}{N}] \quad (11)$$

$$Rs = Ra\left(aT_{mean}{}^2 + bT_{mean} + c(T_{max} - T_{min})^2 + d(T_{max} - T_{min}) + eD + fP + gRH_{mean} + h\frac{n}{N} + i\right) \quad (12)$$

Where, T_{mean} and RH_{mean} are average air temperature ($°C$) and relative humidity (RH%), respectively. RH_{max}, RH_{min}, D (mb) and P (mm) are maximum relative humidity, minimum relative humidity, saturation deficit and precipitation, respectively. *"a", "b", "c", "d", "e", "f", "g", "h"* and *"I"* are models constants. The calibrated values of above constants are presented in Table 1.

Table 1: Calibrated constants for the models in the study station

Model	Model Constants								
	a	b	c	d	e	f	g	h	i
1	0.1665								
2	0.2204	0.5307							
3	0.1514	0.0299	0.4831						
4	0.2165	0.0044	0.4356						
5	0.1958	0.0043	0.0099	0.4224					
6	0.2097	0.0090	0.2446	0.0585					
7	0.2059	0.0066	0.4614	-0.0031					
8	0.1470	0.0294	0.0010	0.4131					
9	-0.0144	0.1193	0.2265	0.4832	-1.2794				
10	0.1593	0.0385	0.1611	0.1086	0.0046	0.1816			
11	0.2185	0.0088	0.1559	0.1273	-0.0068	0.1844			
12	-0.0002	0.0084	0.0002	-0.0026	-0.1342	-0.0007	-0.0006	0.4314	0.2652

The values of statistical indices including RMSE, MBE, NSE and $R^2$are shown in table 2 for all 12 models. For statistical analysis, it was assumed that the best methods were those that yielded the lowest RMSE and $|MBE|$ and highest value of NSE and R^2. Based on Table 2, all recommended models except model 1 show an acceptable accuracy. The minimum and maximum amounts of RMSE and R^2belong to model 12 and model 1, respectively.
The model 12 was found to be the most accurate model for the prediction of global solar radiation in study station with RMSE, MBE, NSE and R^2 values of 1.915 MJ/m²/d, -0.212 MJ/m²/d, 0.924 and 0.933, respectively. Results confirmed that meteorological variables such as precipitation, daily mean air temperature, square root of the maximum and minimum air temperature differences, daily averaged relative humidity, saturation deficit and relative sunshine durations could be used to reasonably estimate the daily global solar radiation. After the model 12, model 11 could estimate the daily global radiation with relatively high accuracy and is therefore recommended to estimate the global solar radiation when the RH, P and D are

unavailable. The model 2 is simple and acceptable for radiation estimation, however model 12 is accurate and complex and it can be used when there are many meteorological data.

Table 2: The Statistical indices of investigated models

Model	Index			
	RMSE	MBE	NSE	R^2
1	3.857	-0.186	0.697	0.696
2	2.324	-0.131	0.884	0.881
3	2.292	-0.153	0.899	0.893
4	2.037	-0.226	0.916	0.915
5	2.033	-0.230	0.916	0.915
6	2.269	-0.156	0.902	0.897
7	2.023	-0.224	0.917	0.916
8	2.292	-0.153	0.893	0.893
9	3.443	-0.302	0.764	0.784
10	2.246	-0.134	0.901	0.897
11	1.989	-0.188	0.922	0.919
12	1.915	-0.212	0.924	0.933

The values of measured and predicted global solar radiation by models 1 (the least accurate model) and 12 (the most accurate model) during 2001 to 2011 are compared as shown in Figure 3. As it can be seen from this figure, the estimated values of solar radiation using model 1 are not fairly close to the measured values as indicated by the values of RMSE, NSE and R^2 as 3.857, 0.697 and 0.696, respectively.

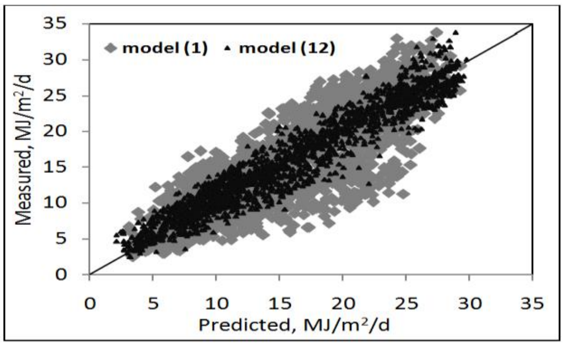

Figure 3: Comparison between measured and predicted global solar radiation by model 1 and 12 from 2001 to 2012.

CONCLUSIONS

Calibration of Angstrom-Prescott model showed that the values of "a" and "b" coefficients are 0.2204 and 0.5307, respectively. In addition, the value of "a" coefficient in Hargreaves model calibrated as 0.1665 $C^{-0.5}$. Statistical results indicated that the Angstrom-Prescott model accuracy is more than Hargreaves model in the study region. Ten new empirical global solar radiation models based on available meteorological variables were developed using daily measured solar radiation data at Tabriz station. Results confirmed that meteorological variables such as precipitation, daily mean air temperature, square root of the maximum and minimum air temperature differences, daily averaged relative humidity, saturation deficit and relative sunshine durations could be used to reasonably estimate the daily global solar radiation. Results of statistical analysis suggest that models 11 and 12 presented in this paper are the most accurate models amongst the solar radiation models, which are based on meteorological data and sunshine hours. Therefore, these models are recommended to be used in Tabriz region for estimation of solar radiation with higher accuracy.

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