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Solar Radiation Estimation from Rainfall and Temperature Data in Arid and Semi-arid Climates of Iran

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Abstract

Precipitation and air temperature data, only, are often recorded at meteorological stations, with radiation being measured at very few weather stations, especially in developing countries. Therefore there arises a need for suitable models to estimate solar radiation for a completion of data sets. This paper is about an evaluation of eight models for an estimation of daily solar radiation (Q) from commonly measured variables in six synoptic stations of Iran, namely: Mashhad, Kerman, Tabriz, Esfehan, Hamedan and Zanjan using daily rainfall and temperature data for a duration of three years of 2000, 2001 and 2002. These stations represent several arid and semiarid sub-climates of Iran as based on extended-De Martonne climatic classification (semiarid-cold: Mashhad and Tabriz, arid-cold: Esfehan, Kerman, semiarid-extracold: Hamedan and Zanjan). The STATISTICA (ver. 6.0) software was employed for non-linear multivariate regression. The results indicated that most of the models overestimated in lower values of solar radiation while underestimating in the higher ranges, indicating a systematic error. Performance of the models was evaluated based on the Root Mean Square Errors (RMSE) as well as R^2. RMSE ranged from 1.14 to 7.76 Cal $cm^{-2}min^{-1}$ for the whole data range and in all the six stations. Among the eight models, the Richardson model rendered the best agreement with the measured data in Kerman and Zanjan stations. In case of Hamedan station, Bristow and Campbell model was the most suitable. As for Tabriz station, De Jong and Stewart model using rainfall and range of daily temperature data led to the best performance. In Mashhad station, McCaskill equation can be recommended. Analysis of the data in Esfehan station showed no significant difference among the models. Due to variation in equations' performances, to come to valid conclusions and to choose the most suitable radiation models, further study would be required from other climatic regions the country.

Keywords: Radiation models; Rainfall; Solar radiation; Temperature

1. Introduction

Many agricultural and environmental studies and their following applications require sets of complete weather data including solar radiations. Studies using dynamic simulation models on climate change, tailoring crop management practices to expected weather (Mavromatis et al., 2002), yield forecasting (Jagtap et al., 2002) as well as agronomic and hydrological practices are some examples.

Weather variables as inputs can have significant impact on simulation model estimates (Aggarwal, 1995), particularly when due to introduced errors arising from supplementary estimated data (Rivington et al., 2003, 2005). Lack of incident solar radiation is a significant impediment for most of these models, especially crop models (Bindi and Miglietta, 1991). The number of weather stations recording Global Solar Radiation (GSR) is limited as compared to the number of stations, recording air temperature and precipitation. The need for GSR recordings has led researchers to the development of a number of formulae and methods for simulating such data. The available methods include stochastic weather generators, satellite images and empirical models. The latter

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vary in sophistication from simple empirical formulae based on common climatic data, to complex radiative transfer schemes. Using empirical methods to estimate GSR at a specific site requires the development of a set of equations that relate solar transmissivity to daily observations of minimum and maximum air temperature using site-specific empirical parameters (Donatelli et al., 2003). Sabbagh (1971) estimated solar radiation employing relative humidity, sunshine hours, air temperature, elevation, and longitude data in several regions of Iran. Khalili and Rezai sadr (1997) proposed an exponential equation for estimation of total radiation from relative humidity data. Soltani and Morid (2005) compared Hargreaves-Samani method and artificial neural networks (ANN) in estimation of solar radiation using daily data of four synoptic stations, Iran, the results indicating that ANN was of a better performance than the former. Safaii et al. (2005) estimated solar energy potential in some selected stations in Iran using three different models. The final results of their study revealed that the hybrid model presented the most suitable alternative. Kamali et al. (2006) evaluated eight models for derivation of daily slope diffuse irradiance from daily horizontal diffuse irradiance against recorded slope irradiances in Karaj, Iran. Among the applied models, the Reindl's was of the best agreement with the measured tilted data. Saffaripour and Mehrabian (2006) suggested two simple models for estimation of total solar radiation on horizontal surface in Kerman and Yazd, Iran. The objectives of this study were to evaluate the accuracy and applicability of several models for estimating daily solar radiation (Q) from rainfall and temperature data obtained from six different climate meteorological stations, Iran.

2. Materials and Methods

Three year (2000, 2001 and 2002) daily meteorological data collected at stations Mashhad (36°16´N, 59°38´E), Tabriz (38°05´N, 46°17´E), Kerman (30°15´N, 56°58´E), Esfehan (32°37´N, 51°40´E), Zanjan (36°40´N, 48°29´E), and Hamedan (34°52´N, 48°32´E) were employed to determine the constants of the empirical equations used in this study (Eqs.1 and 3 to 9). These stations are located in different subclasses of arid and semiarid climates of the country as based on extended-De Martonne classification (Khalili, 1997). Figure 1 depicts the spatial distribution of the selected stations. Daily weather data of minimum and maximum temperature, rainfall and solar radiation were obtained from Islamic Republic of Iran Meteorological Organization (IRIMO). After refining the missing or incorrect observations a data base consisting 1096 records of each variable (maximum and minimum temperature, rainfall and actual radiation) for years 2000, 2001 and 2002 were respectively created. Homogeneity of the data was checked through run test.

2.1. Estimation of solar radiation using temperature records

The model suggested by Bristow and Campbell (1984) for estimation of solar radiation (Q) as based on the extra-terrestrial solar radiation (Q_o) and a range of daily air temperature extremes (D) was employed as follows:

$$Q = Q_0 a(1 - \exp(-bD^c)) \quad (1)$$

where: a, b and c are empirical coefficients, determined for the specific site of study, D is diurnal range of air temperature as determined through the following:

$$D = T_{\max} - \frac{T_{\min}(j) + T_{\min}(j+1)}{2} \quad (2)$$

where $T_{\max}$ is the daily maximum temperature (°C), $T_{\min}$(j) and $T_{\min}$(j+1) are the daily minimum temperature (°C) of the same and the next day, respectively.
Two other models of estimating solar radiation (Richardson, 1985 and Hargreaves et al., 1985, respectively) are:

$$Q = Q_o\, a\,(T_{\max} - T_{\min})^b \quad (3)$$

$$Q = Q_o\, a\sqrt{T_{\max} - T_{\min}} + b \quad (4)$$

where a and b are the related coefficients.

2.2. Estimation of Solar Radiation using rainfall

Based on Fourier series, McCaskill (1990, a) reported a method as follows for an estimation of solar radiation using rainfall data:

$$Q=a+b\cos(\theta)+c\sin(\theta)+d\cos(2\theta)+e\sin(2\theta)+ fR_{j-1}+gR_j+hR_{j+1} \quad (5)$$

where θ is the day of the year converted to radian (j*2π/365), j represents day of the year, R the transformed rainfall data and subscripts j-1, j and j+1 referring to the previous, current and the next days while a, b, c, d, e, f, g and h being the coefficients determined through regression. The procedure for calculating transformed data (R) was to encode rain-days, i.e., if P>0, R=1; P=0, R=0. Here P represents precipitation while site specific coefficients (a, b, c, d, and e) represent the seasonal changes of radiation at the study site.

In another study McCaskill (1990, b) related Q to Q_o and rainy day data as follows:

$$Q = a\,Q_o + b\,R_{j-1} + cR_j + d\,R_{j+1} \qquad (6)$$

where a, b, c, and d are regression coefficients and R as defined in Eq.(5). The coefficient a is atmospheric transmissivity with no rainfall recorded on the day, the day before or the day after, b, c and d represents the degrees of radiation reduction for the case of rainy days.

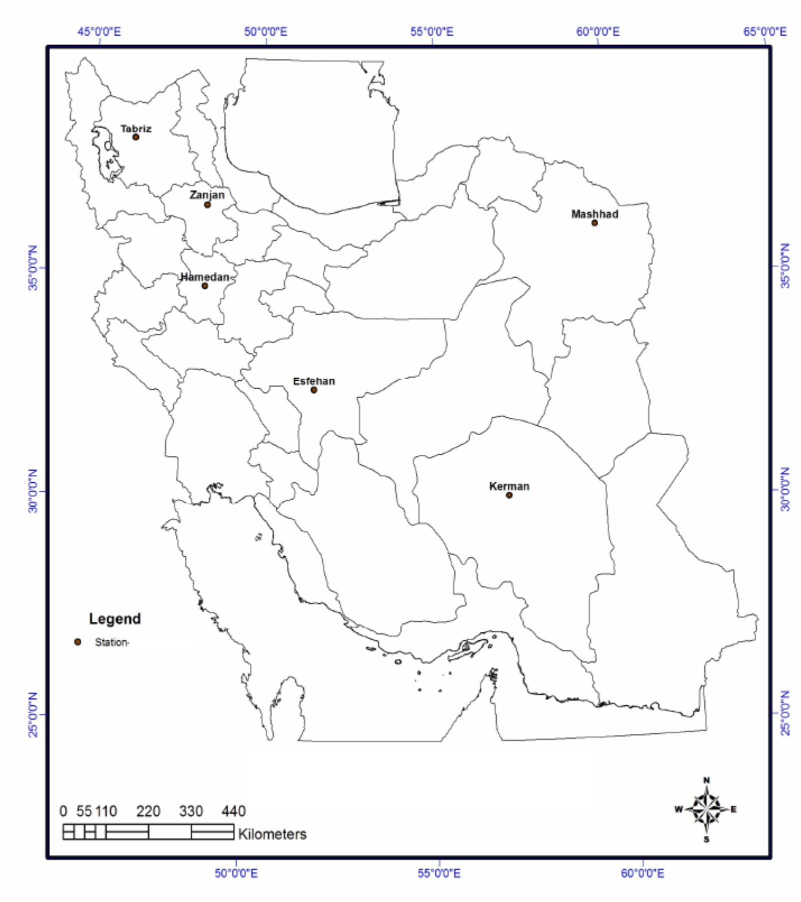

Fig. 1. Geographical distribution of the studied stations

2.3. Estimation of solar radiation while using both rainfall and temperature data

De Jong and Stewart (1993) suggested the following equation for an estimation of solar radiation using precipitation and the range of daily temperature:

$$Q = a\,Q_o\,D^b\,(1 + cP + dP^2) \qquad (7)$$

where D is defined as in equation 1 and P is the total precipitation (mm). Hunt et al. (1998) proposed the following equation to include the effect of P as an additive formula:

$$Q = a\,Q_o\sqrt{T_{max} - T_{min}} + b\,T_{max} + cP + dP^2 + e \qquad (8)$$

where a, b, c, d, and e are the coefficients.

By analyzing data sets from Australia, Liu and Scott (2001) proposed an equation in the form of:

$$Q = Q_0 a(1 - \exp(-bD^c)) + dR_{j-1} + eR_j + fR_{j+1} + g \qquad (9)$$

where a, b, c, d, e, f and g are the coefficients. D and R are defined in Eqs. (1) and (5) respectively.

2.4. Calculation of daily extraterrestrial solar radiation (Q_o)

The equation given by Gates (1980) was employed to determine each day's Q_o as a function of site latitude as follows:

$$Q_0 = 86400\,S_0\,(\bar{d}/d)^2 (h_s \sin f \sin\delta + \cos\varphi \cos\delta \sin h_s)/10^6\pi \qquad (10)$$

where S_o is the solar constant (1360 $w.m^{-2}$), $\overline{d}$ and d the mean and actual values of the distance from sun to earth, respectively; h_s is the half day length, φ the latitude of the location of interest, and δ is the solar declination (δ, φ and h_s are in radians). Due to minor deviations of $(\overline{d}/d)^2$ from unity, it can be taken as unity (Gates, 1980). The term h_s can be derived from the equation suggested by Campbell and Diaz (1988) as:

$$h_s = \pi/2 - ATAN(X/\sqrt{(1-X^2)} \quad (11)$$

ATAN is arctangent and

$$X = \sin\phi \sin\delta / (\cos\phi \cos\delta) \quad (12)$$

$$\delta = 0.39785 \sin(4.869 + 0.0172 J_d + 0.0334 \sin(6.224 + 0.0172 J_d)) \quad (13)$$

where J_d represents the day of the year (Julian).

As for nonlinear multivariate regression, to determine the constants of equations, STATISTICA (ver.6.0) software was employed. In order to overcome the seasonal heterogeneity of error, equations were divided by Q_o. Goodness of fit for evaluation of the models was assessed through determination coefficient (R^2) between the estimated and measured Q and the root mean square error (RMSE) associated with the estimations.

Index of agreement (d) proposed by Willmot (1982) was employed to evaluate the models, performance, the value of d being calculated as follows:

$$d = 1 - [\Sigma(P-O)^2 / \Sigma(|P-\overline{O}| + |O-\overline{O}|)^2], \; 0 \le d \le 1 \quad (14)$$

where Ō is the mean of observed values, P is the predicted value and O the observed one.

In order to test significance of slope and intercept of regression line between observed and predicted values, a statistical test with the following hypothesis was performed:

$$H_0 \begin{cases} a = 0 \\ b = 1 \end{cases} , \quad H_1 \begin{cases} a \neq 0 \\ b \neq 1 \end{cases}$$

Following a calculation of t student values, they were compared to critical value of t corresponding to a level of significance of 5% and a degree of freedom of n-2 (n: number of observations, i.e.365). If calculated t is greater than the table value (t_{Cr}=1.96), then the null hypothesis (H_0) is rejected (Kottegoda and Rosso, 1997).

3. Results

The derived values of each coefficient used in eight the models for the six stations are shown in Table 1 to 6. These data were used to compare the model performance by comparing the obtained with the recorded daily solar radiation data for the years 2000, 2001 and 2002 at a same station. The performance of the eight models is presented in Figure 2 (case of Mashhad station as an example) and in tables 7 and 8. It has been noted that higher correlation coefficient values do not necessarily coincide with lower RMSEs (Mandal, et al., 2003). The calculated values of t-student for slope and intercept of regression line between observed and predicted radiation data are presented in table 9.

Table 1. Values of constants, used in different models in Mashhad station

Station	Mashhad							
Equation	a	b	c	d	e	f	g	h
1	1156.67	690.32	274.3					
3	816.82	0.093						
4	145.71	213.49						
5	432.45	-119.57	-12.98	-21.75	8.27	-9.36	-67.33	-3.31
6	1040.71	29.269	-45.24	23.404				
7	0.6	0.225	0.223	0.225				
8	109.99	2.268	1.3762	-0.2119	212.879			
9	459.13	32.39	-427.08	-116.125	-140.05	-103.127	557.833	

Table 2. Values of constants, used in different models in Kerman station

Station	Kerman							
Equation	a	b	c	d	e	f	g	h
1	1246.65	576.065	206.864					
3	562.919	0.4638						
4	231.241	20.642						
5	541.663	-252.827	-22.147	-16.826	-10.863	-28.9097	-83.472	-18.321
6	1258.158	-0.6123	-74.190	-3.0145				
7	643.177	0.321	-0.0191	0.0003				
8	153.381	1.948	-1.57387	0.0008	108.523			
9	232.1	217.432	-187.63	-114.125	-112.047	-118.93	546.83	

Table 3. Values of constants, used in different models in Tabriz station

Station				Tabriz				
Equation	a	b	c	d	e	f	g	h
1	999.41	576.065	212.898					
3	316.090	0.4638						
4	274.959	20.642						
5	301.327	-252.827	-31.318	42.462	-32.998	159.810	79.722	4.168
6	1040.646	-0.6123	-71.586	-35.478				
7	458.146	0.321	-0.3561	0.0031				
8	239.053	1.948	-10.326	0.606	31.359			
9	129.096	217.432	-215.284	-116.722	-115.966	-129.741	529.606	

Table 4. Values of constants, used in different models in Esfahan station

Station				Esfahan				
Equation	a	b	c	d	e	f	g	h
1	1211.373	680.336	204.345					
3	873.760	0.1180						
4	240.420	106.088						
5	511.314	-204.923	14.538	-34.907	-4.558	-51.552	-162.189	-73.832
6	1222.912	-17.377	-29.452	-29.702				
7	984.353	0.075936	-0.0241	0.0004				
8	240.699	0.0475	6.0546	-0.620	104.035			
9	274.634	217.436	-215.284	-116.722	-115.966	-129.711	529.606	

Table 5. Values of constant, used in different models in Zanjan station

Station				Zanjan				
Equation	a	b	c	d	e	f	g	h
1	1058.28	607.904	217.007					
3	429.837	0.3318						
4	220.100	86.6134						
5	420.1547	-192.247	10.495	0.0617	26.895	17.4675	-87.5005	7.714
6	1097.784	11.275	-91.17	-18.31				
7	657.699	0.1840	-0.0486	0.0008				
8	224.735	-0.8659	-13.2755	0.1858	103.90			
9	118.9521	62.4524	-463.366	-43.2972	-135.829	-74.245		

Table 6. Values of constant, used in different models in Hamedan station

Station				Hamedan				
Equation	a	b	c	d	e	f	g	h
1	1299.634	714.692	212.796					
3	711.319	0.2145						
4	249.113	120.185						
5	540.23	-222.250	51.466	12.958	-1.5066	26.616	-131.587	-57.236
6	1331.053	49.07	-119.082	-35.982				
7	1049.602	0.0825	-0.054	0.0014				
8	310.911	-4.6727	-9.144	0.2701	-119.793			
9	570.096	73.865	216.023	-27.454	-113.887	-211.220	348.62	

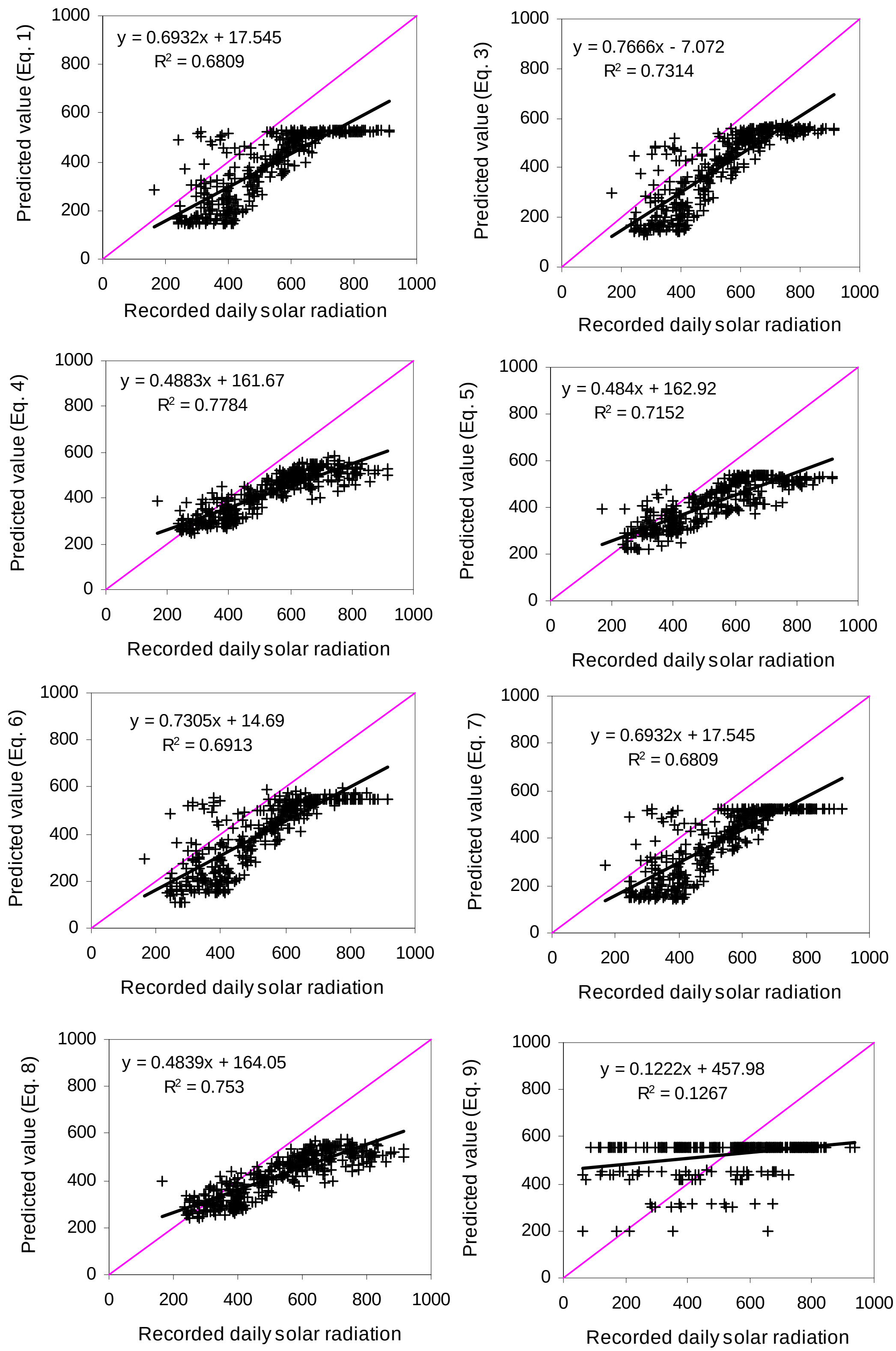

Fig. 2. Relationship between recorded and predicted daily solar radiation (Cal $Cm^{-2}min^{-1}$) at Mashhad station for year 2002

Table 7. Statistics for testing the models, performance in Mashhad, Kerman and Esfehan

Station		Mashhad			Kerman			Esfahan		
Eq. No.	Year	R^2	RMSE (Cal cm^{-2} min^{-1})	d Index	R^2	RMSE (Cal cm^{-2} min^{-1})	d Index	R^2	RMSE (Cal cm^{-2} min^{-1})	d Index
1	2000	0.637	4.302	0.841	0.747	2.342	0.921	0.230	3.331	0.587
	2001	0.753	2.127	0.929	0.652	3.0831	0.885	0.393	3.128	0.725
	2002	0.681	4.115	0.858	0.407	4.672	0.736	0.488	2.442	0.794
3	2000	0.742	4.072	0.859	0.805	2.621	0.943	0.233	3.457	0.597
	2001	0.783	1.148	0.951	0.708	2.280	0.907	0.389	2.473	0.728
	2002	0.731	3.612	0.852	0.498	4.912	0.788	0.488	2.440	0.808
4	2000	0.765	2.576	0.901	0.801	2.511	0.933	0.229	4.737	0.572
	2001	0.807	1.819	0.958	0.694	4.141	0.889	0.358	3.842	0.688
	2002	0.778	2.803	0.903	0.493	5.212	0.780	0.443	3.172	0.789
5	2000	0.806	2.530	0.903	0.762	2.801	0.921	0.226	5.786	0.612
	2001	0.815	1.332	0.961	0.645	3.516	0.873	0.354	4.875	0.724
	2002	0.715	2.437	0.897	0.609	3.912	0.833	0.502	3.962	0.837
6	2000	0.638	4.931	0.851	0.771	2.711	0.932	0.234	4.372	0.601
	2001	0.758	2.405	0.947	0.677	4.121	0.895	0.392	3.548	0.733
	2002	0.691	2.530	0.890	0.435	5.202	0.863	0.506	2.545	0.811
7	2000	0.638	2.432	0.845	0.795	2.112	0.940	0.235	4.758	0.598
	2001	0.753	2.419	0.929	0.696	3.713	0.903	0.382	3.618	0.724
	2002	0.681	3.752	0.859	0.472	4.502	0.784	0.486	3.107	0.815
8	2000	0.724	3.140	0.861	0.789	3.124	0.931	0.231	5.818	0.573
	2001	0.814	2.437	0.959	0.682	4.572	0.884	0.358	4.972	0.688
	2002	0.753	2.119	0.901	0.563	4.102	0.813	0.438	4.605	0.789
9	2000	0.241	4.732	0.624	0.241	4.027	0.503	0.076	5.542	0.244
	2001	0.119	6.321	0.228	0.119	6.248	0.376	0.061	6.121	0.234
	2002	0.126	5.062	0.321	0.127	6.137	0.395	0.093	4.551	0.392

Table 8. Statistics for testing the models, performance in Tabriz, Hamedan and Zanjan

Station		Tabriz			Hamedan			Zanjan		
Eq. No.	Year	R^2	RMSE (Cal cm^{-2} min^{-1})	d Index	R^2	RMSE (Cal cm^{-2} min^{-1})	d Index	R^2	RMSE (Cal cm^{-2} min^{-1})	d Index
1	2000	0.649	4.668	0.633	0.610	3.342	0.807	0.587	4.382	0.835
	2001	0.781	3.846	0.934	0.501	3.052	0.773	0.617	3.713	0.866
	2002	0.724	3.212	0.915	0.601	2.440	0.826	0.524	3.959	0.835
3	2000	0.674	4.615	0.681	0.370	4.723	0.703	0.639	3.151	0.873
	2001	0.852	2.986	0.953	0.508	1.022	0.742	0.704	1.567	0.911
	2002	0.825	3.268	0.943	0.695	3.541	0.849	0.633	2.907	0.884
4	2000	0.764	5.012	0.673	0.387	4.815	0.720	0.639	3.182	0.860
	2001	0.853	3.117	0.952	0.416	4.022	0.736	0.714	2.641	0.905
	2002	0.827	3.842	0.941	0.661	3.726	0.845	0.652	2.915	0.887
5	2000	0.408	6.402	0.708	0.406	4.522	0.731	0.644	2.905	0.859
	2001	0.571	5.212	0.857	0.520	3.912	0.779	0.716	2.714	0.899
	2002	0.453	5.021	0.795	0.649	2.824	0.841	0.589	2.829	0.862
6	2000	0.659	5.780	0.664	0.371	5.028	0.704	0.627	3.942	0.865
	2001	0.823	3.419	0.943	0.462	4.951	0.758	0.693	3.324	0.903
	2002	0.801	2.842	0.936	0.644	4.012	0.843	0.653	4.027	0.856
7	2000	0.663	4.723	0.672	0.382	4.705	0.711	0.649	4.312	0.876
	2001	0.850	2.340	0.952	0.431	3.846	0.754	0.719	2.041	0.915
	2002	0.829	2.108	0.945	0.670	3.092	0.853	0.628	3.248	0.882
8	2000	0.681	4.752	0.678	0.377	3.452	0.721	0.663	2.992	0.872
	2001	0.850	3.431	0.950	0.536	2.812	0.784	0.740	1.912	0.914
	2002	0.827	3.821	0.943	0.646	2.127	0.841	0.657	2.762	0.890
9	2000	0.079	7.764	0.319	0.298	5.302	0.697	0.220	4.272	0.463
	2001	0.180	7.012	0.579	0.403	4.668	0.722	0.194	4.926	0.436
	2002	0.190	6.928	0.602	0.496	4.027	0.793	0.108	6.182	0.421

Table 9. Results of t-test for slope and intercept of regression line between observed and predicted values of radiation in studied stations

		a			b			$t_{cal}(a)$			$t_{cal}(b)$		
Station	Eq. No. \ Year	2000	2001	2002	2000	2001	2002	2000	2001	2002	2000	2001	2002
Esfahan	1	0.2768	0.3983	0.4993	356.3	295.6	249.8	23.6	20.5	18.0	27.2	23.2	19.3
	3	0.2891	0.4091	0.5175	350.1	289.5	237.0	22.4	19.4	16.6	25.8	22.0	18.2
	4	0.2594	0.3531	0.4625	371.9	323.4	264.1	26.3	23.4	20.7	29.7	26.1	22.7
	5	0.3242	0.435	0.5749	322.7	265.2	201.7	18.0	15.7	13.7	21.4	18.3	15.4
	6	0.2591	0.4167	0.5224	344.9	284.4	236.1	21.5	18.8	16.5	24.9	21.4	17.9
	7	0.2905	0.407	0.5245	349.6	291.5	233.6	22.4	19.4	16.6	25.8	22.0	18.1
	8	0.2597	0.3539	0.4633	371.8	323.6	263.6	26.3	23.5	20.6	29.7	26.1	22.5
	9	0.0744	0.0716	0.1083	459.5	461.9	445.7	59.9	56.1	54.7	68.4	62.7	58.8
Hamdean	1	0.5236	0.4281	0.6464	204.1	296.8	231.9	12.8	21.4	17.5	18.8	23.8	12.8
	3	0.7167	0.4786	0.7453	85.7	265.0	82.9	4.9	17.7	4.6	10.3	20.1	6.8
	4	0.6551	0.4351	0.6743	130.3	293.6	220.5	8.4	22.2	18.1	14.0	24.7	12.8
	5	0.7105	0.5025	0.7029	98.7	258.5	207.8	6.4	20.7	16.0	11.8	22.9	11.0
	6	0.7197	0.5025	0.7351	85.8	254.7	188.1	4.9	18.0	13.6	10.2	20.3	9.2
	7	0.7245	0.4835	0.7497	83.7	263.7	181.2	5.0	18.4	13.7	10.3	20.8	9.1
	8	0.6886	0.4559	0.6631	125.4	282.2	229.0	8.1	21.7	18.2	13.5	24.2	12.9
	9	0.5106	0.3168	0.5006	223.2	323.5	295.1	14.8	29.6	23.2	20.5	33.0	18.9
Kerman	1	0.7747	0.7697	0.4674	131.9	142.6	254.5	10.4	9.2	14.0	9.5	7.8	18.0
	3	0.8901	0.8469	0.5410	71.9	102.4	209.4	5.8	6.9	11.5	4.8	5.4	15.5
	4	0.7661	0.7111	0.7420	142.4	177.3	255.8	13.3	13.7	16.6	11.7	11.7	21.0
	5	0.7502	0.7152	0.5380	149.2	176.1	219.0	12.6	12.1	15.9	11.4	10.2	20.6
	6	0.8403	0.8206	0.501	96.4	116.2	233.5	7.5	7.5	12.7	6.7	6.0	16.7
	7	0.8782	0.8359	0.5344	77.8	106.0	213.1	6.2	7.0	11.7	5.2	5.6	15.7
	8	0.8685	0.7166	0.5144	138.8	176.9	231.3	12.4	13.2	15.8	11.1	11.0	20.5
	9	0.1981	0.1527	0.1222	430.2	458.9	457.9	43.5	40.3	44.3	43.5	38.9	52.2
Mashhad	1	0.1009	0.8391	0.6932	345.8	-1.39	17.48	14.7	-0.1	1.3	11.4	6.4	12.3
	3	0.0571	0.919	0.7666	383.8	-22.1	-7.07	17.2	-1.8	-0.5	12.6	3.2	9.6
	4	0.0706	0.5698	0.4883	401.8	162.7	161.67	29.2	23.1	21.4	20.2	29.5	37.5
	5	0.1381	0.5905	0.484	381.8	152.4	162.9	26.7	21.5	18.4	18.0	27.7	32.2
	6	0.0484	0.878	0.7305	388.1	-2.96	14.7	18.0	-0.2	1.0	13.2	4.7	10.5
	7	0.0239	0.8391	0.6932	379.7	-1.4	17.5	18.6	-0.1	1.3	14.3	6.4	12.3
	8	0.883	0.5778	0.4839	396.4	159.5	164.1	10.4	22.8	20.4	0.9	29.1	35.5
	9	0.1488	0.216	0.1222	460.9	425.7	457.9	34.5	39.3	0.3	19.0	34.9	0.3
Tabriz	1	0.2934	0.792	0.7673	250.1	103.1	114.7	33.6	9.5	21.5	23.6	12.5	12.58
	3	0.3494	0.9609	0.929	220.4	40.5	54.5	27.4	1.9	3.2	18.4	5.1	6.5
	4	.3365	0.9258	0.895	228.5	55.4	68.7	29.0	3.7	4.9	19.8	7.3	8.6
	5	0.393	0.8661	0.8033	180.7	48.9	83.9	24.4	3.4	4.3	14.4	3.3	4.9
	6	0.3285	0.9002	0.8904	203.4	62.9	66.2	29.1	4.5	4.7	20.0	7.6	7.7
	7	0.3388	0.9405	0.9148	227.5	49.3	58.6	28.1	2.9	3.9	19.1	6.3	7.3
	8	0.3413	0.9218	0.9062	26.96	58.3	62.9	15.5	3.9	4.3	10.6	7.6	7.8
	9	0.1153	0.3174	0.3699	301.48	240.7	208.8	43.0	19.2	15.8	28.9	18.0	14.1
Zanjan	1	0.6033	0.642	0.6879	145.1	142.7	139.4	17.1	14.3	9.1	13.2	12.7	9.8
	3	0.740	0.7973	0.8646	78.891	74.52	63.3	10.5	7.9	4.0	6.7	6.5	4.5
	4	0.6484	0.7021	0.7666	127.6	123.4	110.8	16.3	13.5	8.0	12.5	12.5	9.2
	5	0.6401	0.667	0.7146	131.3	138.7	130.9	17.4	15.8	9.2	13.4	14.7	10.2
	6	0.7167	0.7394	0.7852	89.4	102.8	94.9	11.6	10.7	6.0	7.7	9.4	6.3
	7	0.7337	0.7817	0.845	83.7	83.1	73.1	11.2	9.0	4.6	7.4	7.7	5.2
	8	0.675	0.7158	0.7841	115.5	118.6	103.9	15.4	13.1	7.3	11.6	12.2	8.5
	9	0.2038	0.1559	0.1696	313.3	353.7	337.1	45.4	49.0	32.6	37.7	46.0	31.9

Aa and b are slope and intercept, respectively, of regression between predicted and observed values, terms $t_{cal}(a)$ and $t_{cal}(b)$ are calculated values of t-student statistics for slope and intercept, respectively.

4. Discussion and Conclusion

The performance of the models varies for the three years (2000, 2001, and 2002). One possibility is that there may be a systematic error occurring in all models which results in a relatively poor performance in most of them. Besides, measurement errors may also be involved. The 1:1 line in Fig. 2 indicates that most of the models overestimated values in the lower range of solar radiation but underestimated them in the higher ranges (such a trend was observed in most of the other study regions which indicates the fact that a major portion of errors is coming from systematic ones). Among the eight applied models, equation 5 for Mashhad had higher values of R^2 together with lower RMSEs over the three years of study (0.779 and 2.09, respectively). This model had the highest average value of d index (0.921). In Kerman station, equation 3 turned out to be the most suitable one with the highest value of R^2 (0.670), lowest RMSE (3.27 cal cm^{-2} min^{-1}) as well as highest d index (0.879) in all three years. In the case of Tabriz, equation 7 bore higher values of R^2 and lower RMSEs.

Equation 1 demonstrated the highest performance with higher values of R^2 and d index (0.571 and 0.802, respectively) in Hamedan. In Zanjan, equation 3 did the best with a RMSE of 2.54 cal cm^{-2} min^{-1}, coefficient of determination over 0.65 and an index of agreement of 0.889. In case of Esfehan station, none of the models performed well and there was no significant difference observed among them, that might be justified by systematic error or some unknown local climatic conditions which must be further serutinized. In general**,** the models using temperature only did a better job in Kerman, Zanjan and Hamedan. In mashhad station, the model using rainfall data only (Eqn.5) yielded the best result. Finally, in Tabriz station equation 7 which uses both temperature and rainfallgained priority in relation to the others. The results of significance test of slope and intercept values (at 5% level of confidence) indicated that in Mashhad station only and for years of 2001 and 2002 (in equations 1,3,6 and 7) the H_1 hypothesis for slope is rejected. In all other stations, there exists a significant difference between line 1:1 and regression line. Based on the obtained results, equations 8 and 9 can not be recommended in the selected stations. Due to variations observed in equations' performance, to come to valid conclusions and to choose the most suitable models for radiation estimation, further scrutinized study would be indispensable at other climatic regions of the country.

References

Aggarwal, P.K., 1995. Uncertainties in crop, soil and whether inputs used in growth models-implications for simulated outputs and their applications. Agric. Syst., 48: 36-384.

Bindi, M. and F. Miglietta, 1991. Estimation of daily global radiation from air temperature and rainfall measurements. J. Climate. Res., 1: 117-124.

Bristow, K.L. and G.S. Campbell, 1984. On the relationship between incoming solar radiation and daily maximum and minimum temperature. Agric. For. Meteorol., 31: 159-166.

De Jong, R. and D.W. Stewart, 1993. Estimation of global solar radiation from common meteorological observations in western Canada. Can. J. Plant. Sci., 73: 509-518.

Donatelli, M., G. Bellocchi and F. Fontana, 2003. RadEst 3: a software to estimate daily radiation data from commonly available meteorological variables. Agric. For. Meteorol., 18: 363-367.

Gates, D.M., 1980. Biophysical ecology. Springer-Verlag, New York, 340 pp.

Hargreaves, G.L., G.H. Hargreaves and J.P. Riley, 1985. Irrigation water requirements for Senegal river basin. J. Irrig. Drain. Eng., ASCE, 111: 265-275.

Hunt, C.A., L. Kuchar and C.J. Swanton, 1998. Estimation of solar radiation for use in crop modeling. Agric. For. Meteorol., 91: 293-300.

Jagtap, S.S. and J.W. Jones, 2002. Adaptation and evaluation of the CROPGRO-soybean model to predict regional yield and production. Agric. Ecosyst. Environ., 93: 73-85.

Kamali, Gh.A., I. Moradi and A. Khalili, 2006. Estimating solar radiation on tilted surfaces with various orientations: a study case in Karaj (Iran). Theor. Appl. Climatol., 84: 235-241.

Khalili, A., 1997. Integrated water plan of Iran. Vol.4:Meteorological studies, Ministry of Power, Iran.

Khalili, A. and H. Rezai sadr, 1997. Solar radiation estimation across Iran using climatic data. Geographical Research Quarterly, 46: 15-35, (In Farsi).

Kottegoda, N.T. and R. Rosso, 1997. Statistics, probability, and reliability for civil and environmental engineers. McGrawHill, NewYork, 735 p.

Liu, D.L. and B.J. Scott, 2001. Estimation of solar radiation in Australia from rainfall and temperature observations. Agric. For. Meteorol., 106: 41-59.

Mandal, U.K., U.S., Victor, K.V., Rao, N.N., Srivastava, and K.P.R. Vittal, 2003. Estimation of solar radiation from temperature and rainfall observations. J. Agrometeorol., 5 (2):15-26.

Mavromatis, T. and J.W. Hansen, 2001. Interannual variability characteristics and simulated crop responses for four stochastic weather generators. Agric. For. Meteorol., 109: 283-296.

McCaskill, M.R., 1990a. An efficient method for generation of full climatological records from daily rainfall. Aust. J. Agric. Res., 41:595-602.

McCaskill, M.R., 1990b. Prediction of solar radiation from rain day information using regionally stable coefficients. Agric. For. Meteorol., 51: 247-255.

Richardson, C.W., 1985. Weather simulation for crop management models. Trans. ASAE, 28: 1602-1606.

Rivington, M., K.B. Mattews and K. Buchman, 2003. Quantifying the uncertainty in spatially explicit land use model predictions arising from the use of substituted climate data. In: Proceedings of MODSIM 2003, Int. congress on modeling and simulation: Integrative modeling of biophysical, social and economic systems for resource management solutions, Vol. 4, 14-17 July, Australia.

Rivington, M., G. Bellocchi, K.B. Matthews and K. Buchan, 2005. Evaluation of three model estimations of solar radiation at 24 UK stations. Agric. For. Meteorol., 132: 228-243.

Sabbagh, J.A. 1977. Estimation of total solar radiation from meteorological data.Solar Energy, 19:307-315.

Safaii, B., M. Khalaji Asadi, H. Taghizadeh, A. Jilavi, G. Taleghani and M. Danesh, 2005. Estimating solar energy potential in Iran and related radiation atlas. J. Nuclear Sci. and Tech., 33: 27-34.

Saffaripour, M.H. and M.A. Mehrabian, Calibration and validation of solar radiation models using empirical data, 16th annual conference of mechanical engineering, Iran, (In Farsi).

Soltani, S. and M. Morid, 2005. Comparison of estimated values of solar radiation by artificial neural networks and Hargreaves-Samani methods. Danesh-e-Keshavarzi (Agricultural Science), 15:69-77, (In Farsi).

Willmott, C.J., 1982. Some comments on the evaluation of model performance. Bul. Amer. Meteorol. Soc., 63: 1309-1313.