Hindawi Publishing Corporation
International Journal of Photoenergy
Volume 2007, Article ID 94786, 7 pages
doi:10.1155/2007/94786

Research Article

General Formula for Estimation of Monthly Mean Global Solar Radiation in Different Climates on the South and North Coasts of Iran

Ali A. Sabziparvar

College of Agriculture, University of Bu-Ali Sina, 65174 Hamedan, Iran

Received 11 April 2006; Revised 14 September 2006; Accepted 25 September 2006

Recommended by Julian Blanco Galvez

Using sunshine duration, cloud cover, relative humidity, average of maximum temperature, and ground albedo as the input of several radiation models, the monthly average daily solar radiation on horizontal surface in various coastal cities of the South (25.23° N) and the North (38.42° N) of Iran are estimated. Several radiation models are tested and further are revised by taking into consideration the effects of relative humidity, ground albedo, and Sun-Earth distance. Model validation is performed by using up to 13 years (1988–2000) of daily solar observations. Errors are calculated using MBE, MABE, MPE, and RMSE statistical criteria (see nomenclature) and further a general formula which estimates the global radiation in different climates of coastal regions is suggested. The proposed method shows a good agreement (less than 7% deviation) with the long-term pyranometric data. In comparison with other works done so far, the suggested method performs a higher degree of accuracy for those of two regions. The model results can be extended to other locations in coastal regions where solar data are not available.

1. INTRODUCTION

Iran has a variety of climates from the South to the North and is located in a region where the potential of global solar radiation is considerably high. Unfortunately, the coverage of solar radiation monitoring sites is not standard to be properly used in energy, agriculture, and other sectors. Total daily solar radiation (R_{sc}) is considered as the most important parameter in the performance prediction of renewable energy systems, particularly in sizing photovoltaic (PV) power and solar heating systems. In addition, R_{sc} data are required for agriculture and building design applications. Thus, solar radiation measurements and estimated R_{sc} data are important tools for many areas of research in Iran. Since solar measurements in coastal regions of Iran are sparse, developing a general simple radiation model for reliable prediction of solar energy in other Iranian coastal locations is required.

So far, a number of formulae and methods have been developed to estimate R_{sc} at different places in the world. Because of the differences in local climate conditions, the suggested radiation models for one location may not successfully apply to other places. The availability of meteorological parameters which are used as the input to radiation models is an important key to choose the proper radiation models at any location. Among all such meteorological parameters, sunshine hours (n), latitude (L), and cloud cover are the most widely and commonly used parameters to predict daily global solar radiation and its components at any location. In the second order of importance, other input parameters such as maximum air temperature ($T_{\max}$), relative humidity (RH), aerosol optical air mass, surface albedo (α), and altitude of the location (h) can influence the total solar radiation at the surface.

Many researchers (e.g., [1]) derived their models by using sunshine hours, relative humidity, latitude, and air temperature. Reddy [1] suggested the use of number of rainy days, sunshine hours, latitude, and a geographical factor (K) as the input to his model. Using sunshine hours, maximum air temperature, latitude, and relative humidity, Sabbagh et al. [2] estimated the global solar radiation at various places. Their method was not capable of predicting the direct and diffuse components of radiation. Paltridge and Proctor [3] employed cloud data and latitude in a model which could predict the direct and diffuse daily solar radiation at the Earth's surface.

Table 1: Geographical information of the northern and the southern coastal cities (IRAN).

No.	City	Lat. (degree N)	Long. (degree E)	Alt. (m)	Climate type ©	Regional site code	Remarks
1	Astara	38.42	48.86	−18	Cfa	40709	NC
2	Bandar Anzali	37.47	49.47	−26	Cfa	40718	NC
3	Rasht	37.20	49.65	37	Cfa	8811	NC
4	Ramsar (*)	36.90	50.67	−20	Cfa	40732	NC(*)
5	Babolsar	36.72	52.65	−21	Csa	40736	NC
6	Noshahr	36.65	51.50	−21	Cfa	40734	NC
7	Bandar Mahshahr	30.55	49.15	6	BSh	40832	SC
8	Abadan	30.42	48.25	7	BSh	40831	SC
9	Bushehr (*)	28.98	50.83	20	BWh	40858	SC(*)
10	Bandar Abbas (*)	27.22	56.37	10	BWh	40875	SC(*)
11	Kish (Isl.)	26.65	53.97	30	BWh	40882	SC
12	Bandar Lengeh	26.58	54.83	14	BSh	40883	SC
13	Syree (Isl.)	25.88	54.48	4	BWh	40889	SC
14	Abu-Musa (Isl.)	25.83	54.83	7	BWh	40890	SC
15	Jask (*)	25.63	57.77	5	BWh	40893	SC(*)
16	Chabahar	25.23	60.50	8	BWh	40898	SC

SC: Southern coast
NC: Northern coast
BSh: Hot Semiarid Steppe
Csa: temperate Mediterranean climate
(*): solar radiation site
Cfa: wet all seasons
BWh: hot arid desert
(Isl): island
©: based on Köppen's climate classification [13].

Using the above model, Daneshyar [4] suggested a modified version of Paltridge and Proctor model for Tehran (Iran). Jafarpur and Yaghoubi [5] estimated monthly and annual radiation for Shiraz (Iran). In another work, Samimi [6] developed a height-dependent model by the use of A. B. Meinel and M. P. Meinel [7] work. To predict the daily radiation for different places in Iran, he applied Sun-Earth correction factor, cloud factor, sunshine hours, and altitude of the location. Following his work, Yaghoubi and Sabazevari [8] used sunshine hours in order to calculate monthly clearness index (CI) for Shiraz (Iran).

Rehman [9] compared estimated daily radiation from 16 different radiation models for 41 cities in Saudi Arabia. He used latitude, altitude, sunshine hours, and albedo in his work. Other studies such as those of Al-Mohammad [10], Almorox et al. [11], and Zhou et al. [12] employed mainly sunshine hours for predicting surface global solar radiation for different places in the world.

Because of the differences in climate conditions of South and North Iran (see Table 1), it is necessary to test various radiation models in order to achieve the best radiation model applicable to either coastal region.

The objectives of the present research are (1) to estimate the monthly average daily global surface radiation (R_{sc}) in various locations of the South and the North coasts of the country where the population, industrial activities, agricultural productions, and energy demand are high, but solar energy measurements are not widely available; (2) to evaluate several radiation models in different climates of coastal regions to obtain a general formula applicable to either coastal regions and further to revise them by taking into consideration the effects of other parameters; and (3) to compare the total annual and seasonal variations of global radiation in different climates of South and North coasts in order to be used by energy policy makers.

It should be noted that the average total number of clear-sky days in the North and the South coasts are 90 and 260 days per year, respectively, while the number of overcast days are 155 (North) and 20 (South) days per year. On average, the total annual number of rainy days in the North and South are 135 and 25 days per year, respectively. The mentioned meteorological data imply a significant difference in climate conditions.

2. DATA AND METHODOLOGY

2.1. Data

After quality control and necessary statistical tests, various hourly and daily observed meteorological data were used as the input of the employed radiation models (see Nomenclature). Measured data were mainly taken from Islamic Republic of Iran Meteorological Office (IRIMO) data centre [14] and further averaged to obtain the long-term monthly mean values. Monthly average daily sunshine hours (n) measured by Campbell-Stokes sunshine recorders. Total daily global solar radiations were measured by Kipp & Zonen (CM5) pyranometers and CC1 integrators. A seven-year (1984–1990) monthly mean climatology of surface albedo from International Satellite Cloud Climatology Project (ISCCP C2) was used and interpolated for the locations of interest. The quality control of daily global solar radiation was carried out using necessary statistical tests (i.e., Run-test; higher limits of daily sunshine hours; and higher limits of extraterrestrial daily solar radiation). Other input data were determined as follows.

Maximum sunshine hours (N) from Cooper [15]; total daily extraterrestrial solar radiation (R_{ext}) and hour angle (ω_s) from Iqbal [16]; solar constant (SC) from Royal Meteorological Institute of Belgium [17]; and solar declination angle (δ) from Spencer [18]. Day angles (DA) were modified to midday time when major total daily radiation is received [19]:

$$\mathrm{DA} = \frac{2\pi(\mathrm{DN} - 0.5)}{365}. \tag{1}$$

2.2. Methodology

2.2.1. Method 1: Sabbagh (S)

The advantage of Sabbagh's model [2, equation (2)] is that the required input data are available in most Iranian meteorological sites.

$$R_{\text{sc}}(\mathrm{S}) = 1.53K \cdot \exp\left[L\left(\frac{n}{12} - \frac{\mathrm{RH}^{0.333}}{100} - \frac{1}{T_{\max}}\right)\right], \tag{2}$$

where(K) is the geographical factor, (L) is the latitude of location, (n) is the monthly mean sunshine duration, (RH) is the relative humidity and ($T_{\max}$) is the monthly mean of maximum air temperature. To determine the monthly mean daily radiation in each month, the daily radiation was first computed for all days in each month and then averaged to obtain the monthly averages. In comparison with other literatures which take the middle of each month as the representative of monthly mean, this approach can predict the solar radiation with a higher degree of accuracy.

2.2.2. Method 2: Paltridge (P)

This model can determine the instant and total daily radiation at any location. This model which requires solar zenith angle (θ), day length (N) and cloud factor (CF—see nomenclature and (5) for the definition) as the input, presented by Paltridge and Proctor [3]. This model assumes that the effect of albedo and aerosol optical air mass on surface radiation is small (less than 5%). The hourly direct and diffuse radiation is determined by (3) and (4). It should be stressed that the units of hourly and daily energy shown in methods 1–6 are in $\mathrm{cal} \cdot \mathrm{cm}^{-2}$ (the original units of earlier works).

$$I_{\text{dir}}(\mathrm{P}) = 81.738[1 - \exp(-0.075(90 - \theta))], \tag{3}$$

$$I_{\text{dif}}(\mathrm{P}) = 0.218 + 0.299(90 - \theta) + 17.27\,\mathrm{CF}, \tag{4}$$

where I_{dir} and I_{dif} are the hourly direct and diffuse radiation ($\mathrm{cal} \cdot \mathrm{cm}^{-2} \cdot \mathrm{h}^{-1}$) at the horizontal surface. In this work, for all model calculations, the integrals were simply converted to summation and added up every 15 minutes to obtain total daily global radiation.

Cloud factor (CF) is not normally reported in Iranian meteorological sites. This parameter could be obtained by use of the numbers of cloudy days in each month and the cloud cover. Cloud cover is observed every three hours in three different ranges: (0–2) oktas, (3–6) oktas, and (7–8) oktas. To convert the cloud cover to cloud factor (CF), the following relationship is used [6]:

$$\mathrm{CF} = \frac{n_1 + 4.5n_2 + 7.5n_3}{8(n_1 + n_2 + n_3)}, \tag{5}$$

where n_1, n_2, and n_3 are the total number of days in each month, with zero to 2/8, 3/8 to 6/8, and 7/8 to 8/8 oktas, respectively. It should be pointed out that the influence of CF on hourly (short-term) solar radiation can be pronounced. For long-term climatological studies, the hourly variation of CF has little effect on monthly mean radiation. Though, in this work, for reducing the possible errors the hourly (every 3 hours) CF data were used for the daily integration, using monthly mean CF data instead of hourly data can also provide reasonable results.

2.2.3. Method 3: Daneshyar (D)

Using Paltridge's model, Daneshyar [4] proposed (6) and (7) for the climate conditions of Tehran (Iran). Details of this method are described in [4],

$$I_{\text{dir}}(\mathrm{D}) = 81.738[1 - \exp(-0.075(90 - \theta))], \tag{6}$$

$$I_{\text{dif}}(\mathrm{D}) = 0.123 + 0.181(90 - \theta) + 10.43\,\mathrm{CF}. \tag{7}$$

2.2.4. Method 4: modified Sabbagh (MS)

In this work, to revise the method 1 (S), we applied the following modifications: (1) to consider the effect of Sun-Earth distance, the monthly mean daily radiation of (2) is multiplied by monthly average Sun–Earth distance factor ($\bar{\varepsilon}_m$) [16]; (2) relative humidity (RH) adjustment: a new power was defined for RH by means of the least square method during 1988–2000 until the least discrepancies between the predicted global radiation and experimental data were observed. As a result, the final formula, proposed as the MS method, is presented in (8),

$$\begin{aligned} R_{\text{sc}}(\mathrm{MS}) &= 1.53K \cdot \bar{\varepsilon}_m \\ &\quad \cdot \exp\left[L\left(\frac{n}{12} - \frac{\mathrm{RH}^{0.555}}{100} - \frac{1}{T_{\max}}\right)\right]. \end{aligned} \tag{8}$$

2.2.5. Method 5: modified Paltridge (MP)

(1) In method 2, solar constant of 1353 (W/m2) was used by Paltridge and Proctor [3] while the latest observations reported by [17] shows that the average solar constant is about 1367 (W/m2). Therefore, the total daily global radiation (R_{sc})

Table 2: Minimum, maximum, and mean values of errors for southern cities (Units are in $\text{Mj}\cdot\text{m}^{-2}\cdot\text{month}^{-1}$ except MPE which is in percent).

	RMSE			*MBE*			*MABE*			*MPE*(%)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Method 1 (S)	54	73	65	36	67	49	46	67	57	7.8	12.9	10.4
Method 2 (P)	70	130	102	54	108	82	54	108	82	8.8	18.7	13.7
Method 3 (D)	29	80	55	8	62	36	25	63	43	1.2	10.7	6.1
Method 4 (MS)	47	**62**	56	20	**52**	33	41	**56**	50	5.1	10.1	8.4
Method 5 (MP)	56	125	94	49	102	77	49	102	77	7.9	17.7	12.8
Method 6 (MD)	**25**	73	**49**	**2.5**	54	**29**	**21**	**56**	**38**	**0.4**	**9.3**	**4.8**

were weighted by a factor of 1.0103; (2) monthly mean global R_{sc} was modified by Sun-Earth distance correction factor $(\overline{\varepsilon}_m)$ the same as method 4; (3) surface albedo effect: in arid and semiarid climates, changing the surface albedo (α) at wavelengths greater than $0.4\,\mu$m has small effect on global radiation [3]. In regions where cloud cover and relative humidity are large, multiple-scattering process may increase the diffuse and global surface radiation. For this work, a surface albedo of 0.2 is assumed as the reference albedo [3] and the monthly surface albedo factor (K_{saf}) is determined according to (9). In methods 5 and 6, the model results are modified by K_{saf} factor:

$$K_{saf} = \frac{R_{sc}(\overline{\alpha}_m)}{R_{sc}(\alpha_{0.2})}, \tag{9}$$

$R_{sc}(\overline{\alpha}_m)$ and $R_{sc}(\alpha_{0.2})$ are total daily global radiations computed from relationship described in Rehman [9]:

$$R_{sc}(\alpha) = \frac{R_{ext}\cdot\left(0.1572 + 0.556\frac{n}{N}\right)}{\left(1-\alpha\left(0.25n/N + 0.6(1-n/N)\right)\right)}. \tag{10}$$

Therefore, the final formulation for estimation of monthly average total daily global radiation proposed as modified Paltridge method (MP) is presented in (11),

$$R_{sc}(\text{MP}) = (1.0103)(\overline{\varepsilon}_m)\cdot(K_{saf})\{R_{dir}(\text{P}) + R_{dif}(\text{P})\}. \tag{11}$$

2.2.6. *Method 6: modified Daneshyar (MD)*

In this method, the following modifications were employed to method 3.

(1) Solar constant corrections; the same as method 5.
(2) Sun-Earth distance corrections factor $(\overline{\varepsilon}_m)$; the same as method 4.
(3) Surface albedo modification (K_{saf}); the same as method 5.

Finally, for the prediction of monthly mean daily radiant energy as the modified Daneshyar method (MD), the following relationship is suggested:

$$\begin{aligned} &R_{sc}(\text{MD}) \\ &= (1.0103)(\overline{\varepsilon}_m)(K_{saf}) \\ &\quad\times\left\{(1-\text{CF})\int_{\text{sunrise}}^{\text{sunset}}[81.738[1 - \exp(-0.075(90-\theta))]\cos\theta\cdot dt \right.\\ &\quad\left. + \int_{\text{sunrise}}^{\text{sunset}}[0.123 + 0.181(90-\theta) + 10.43\,\text{CF}]\cdot dt\right\}, \end{aligned} \tag{12}$$

where $R_{sc}(\text{MD})$ is the total daily integrated global radiation in $\text{cal}\cdot\text{cm}^{-2}\cdot\text{day}^{-1}$. The daily integration is accomplished according to method 2.

Table 3: Errors obtained from 6 methods for northern city, Ramsar (Units are in $\text{Mj}\cdot\text{m}^{-2}\cdot\text{month}^{-1}$ except MPE which is in percent).

	RMSE	*MBE*	*MABE*	*MPE*(%)
Method 1 (S)	85	65	73	26.4
Method 2 (P)	81	73	73	21.2
Method 3 (D)	42	35	39	11.3
Method 4 (MS)	75	50	66	21.5
Method 5 (MP)	67	59	59	17.3
Method 6 (MD)	**35**	**27**	**32**	**8.9**

3. MODELS VALIDATION

For each year and every solar station, the model results are evaluated using MBE, RMSE, MPE, and MABE [9] statistical criteria (i.e., for each location, two independent series of dataset consist of up to 12 (months) $\times$ 13 (years) = 156 data). For each method, the errors are computed using measured total monthly global radiation observed at 4 solar radiation sites. The minimum, maximum, and mean errors are given in Table 2. For northern city (Ramsar) where the climate condition is different from southern coast, the errors are shown in Table 3. In evaluating the model results, only mean errors are used.

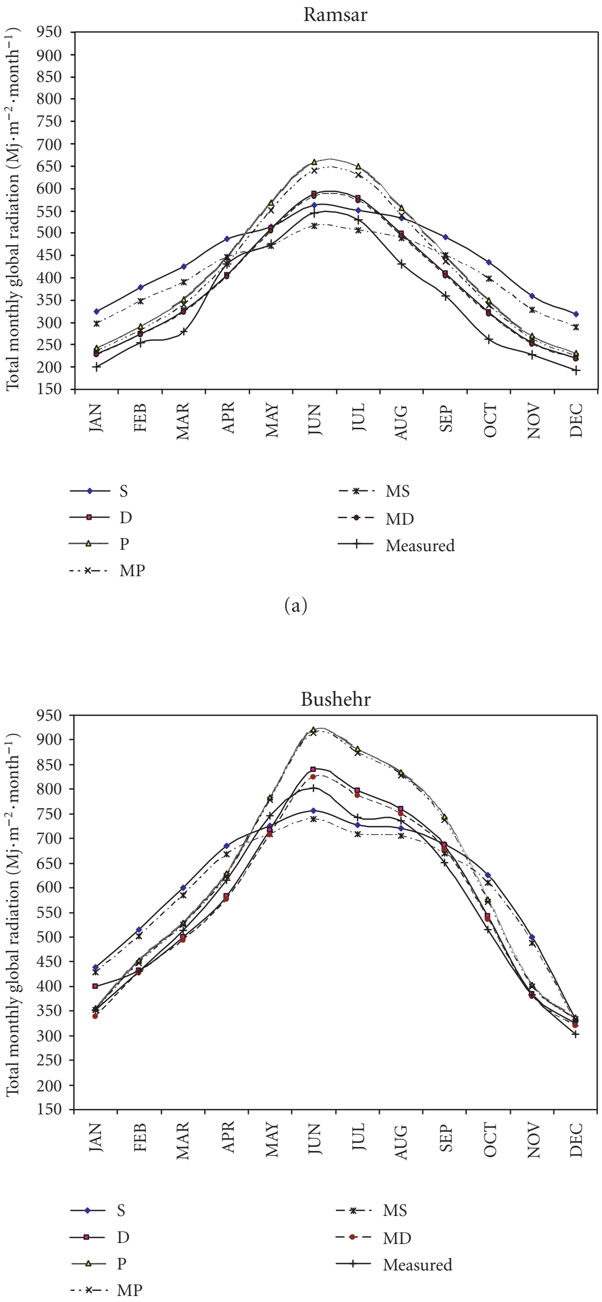

Figure 1: Comparison of the measured and predicted total monthly global radiation (Mj $\cdot$ m^{-2} $\cdot$ month^{-1}) on a horizontal surface for: (a) Ramsar [North] and (b) Bushehr [South].

4. RESULTS AND DISCUSSION

The comparison between the observed total monthly global radiation and predicted total monthly solar energy for selected solar radiation sites is illustrated in Figure 1. As shown, the differences between the observed and the predicted solar energy vary during the course of the year. In winter and autumn when the cloud cover and humidity are high and the ratios of diffuse to direct radiation are large, method (MD) can predict the daily radiation better than other methods. Model results indicate that during the cold seasons, when RH is higher than 55%, methods (S) and (MS) are not good predictors for estimation of daily global radiation in Cfa, BWh, and BSk climates. The overestimation made by (S) and (MS) methods in cold seasons is due to a fact that at high RH, the sensitivity of the (S) and (MS) models for attenuating the incoming radiation is low. Comparison of the model estimations with the observed radiation (Figure 1) during May to August (when $T_{\max}$ is high and RH is low) indicates that Sabbagh model (S) can predict the daily global radiation in southern and northern coasts better than (P) and (D) methods. During summer when the cloud factor (CF) is small and the ratios of direct to diffuse is large, predications made by (P) and (MP) methods lead to larger overestimation compared to other methods.

Comparison of the model errors shown at Tables 2 and 3 indicates that in northern coasts where relative humidity (RH) and cloud cover are larger, the magnitudes of the MPE errors are 4–16% higher than the errors calculated for southern coasts. The relatively higher RH on the northern coasts may cause pronounced differences (errors) in calculation of diffuse radiation. Furthermore, measurement of sunshine hours (n) in foggy, rainy, and cloudy regions (North) has larger errors compared to the measurement made in dry regions (South). However, for the sake of brevity, the errors of southern cities (Table 2) are not presented by site, nevertheless, the pattern of errors (residuals) caused by MD method follows a nearly normal distribution (i.e., random errors or nonsystematic errors). This was not the case for other methods.

The results indicate that at southern and northern coasts, the modified Daneshyar method (MD) with mean MPE error of about 7% performs the best daily and monthly predictions compared to other methods. For either coastal region, the range of the errors performed by (MD) method is reasonable and is within the range of the pyranometers accuracy. In conclusion, we propose the MD method (12) as the general formula for the estimation of daily solar energy in coastal regions with the climate conditions mentioned in Table 1.

On average, in June, the global radiation in southern cities is about 34% larger than northern cities (Table 4). As expected, in December, due to larger solar zenith angles (θ) and shorter day length (N), the differences of global radiation between the South and the North exceed 65%. The model-derived total annual global radiation is also presented in Table 5. As shown, the average of total annual radiation predicted for the southern coasts is 52% larger than annual radiation received in the northern coasts. Accordingly, the mean meridional solar radiation gradient of 4% per 100 km was observed between the southern and the northern coasts. The model results also provide useful information for energy policy makers if they intend to compare and use the incoming solar radiant energy in coastal cities with different climate conditions similar to the coasts of Iran.

Table 4: Best estimation of monthly mean daily global solar radiant energy ($\mathrm{Mj} \cdot \mathrm{m}^{-2} \cdot \mathrm{day}^{-1*}$) predicted by (MD) method.

City		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Astara	(N)	6.90	9.15	10.37	13.88	16.80	21.11	19.98	17.39	14.55	9.74	7.57	6.48
Bandar Anzali	(N)	6.86	9.20	10.07	13.38	16.47	21.07	20.02	17.43	14.00	9.91	7.77	7.57
Rasht	(N)	6.98	9.41	9.99	13.21	16.09	20.15	18.98	16.18	13.42	10.16	7.82	6.69
Ramsar	(N)	7.23	9.57	10.24	13.25	16.14	19.14	18.23	15.72	13.33	9.82	8.28	6.94
Babolsar	(N)	7.61	10.28	11.08	14.50	17.81	20.98	18.94	17.43	15.01	11.54	8.86	7.32
Noshahr	(N)	7.44	9.91	10.91	14.38	16.68	19.77	18.60	15.88	14.59	10.78	8.57	7.15
Bandar Mahshahr	(S)	10.53	14.96	16.18	19.27	22.41	27.25	25.96	24.37	21.99	16.30	12.08	10.12
Abadan	(S)	10.58	15.01	16.22	19.31	22.45	27.25	25.96	24.41	22.03	16.34	12.12	10.16
Bushehr	(S)	11.46	16.02	16.68	20.15	23.96	28.84	26.60	24.20	22.61	17.22	13.25	10.83
Bandar Abbas	(S)	12.16	16.51	17.26	21.40	24.58	27.25	24.24	23.12	22.32	18.18	14.50	13.13
Kish (Isl.)	(S)	12.46	16.89	17.05	21.23	24.33	27.30	24.70	24.16	22.95	18.43	14.80	11.79
Bandar Lengeh	(S)	12.58	16.76	17.51	21.57	24.50	27.25	24.91	23.95	22.95	18.48	15.01	12.16
Syree (Isl.)	(S)	12.50	17.26	17.47	21.11	24.12	27.30	24.83	24.16	23.07	18.81	15.26	11.87
Abu-Musa (Isl.)	(S)	12.33	17.14	17.35	21.28	24.50	27.21	24.87	24.33	23.07	18.85	15.27	11.88
Jask	(S)	12.79	17.39	18.02	21.86	25.25	27.21	23.87	23.28	22.78	18.85	15.42	12.54
Chabahar	(S)	13.13	17.72	18.85	22.45	24.33	26.54	23.24	21.23	22.20	19.14	16.01	13.75

S: South
N: North
*Unit conversion: $(\mathrm{Mj} \cdot \mathrm{m}^{-2} \cdot \mathrm{day}^{-1}) \times (23.88) = (\mathrm{cal} \cdot \mathrm{cm}^{-2} \cdot \mathrm{day}^{-1})$.

Table 5: Total annual global radiant energy at horizontal surface predicted by (MD) method. Units are in $\mathrm{Mj} \cdot \mathrm{m}^{-2} \cdot \mathrm{year}^{-1}$.

City	Total annual
Astara	4681
Bandar Anzali	4676
Rasht	4534
Ramsar	4498
Babolsar	4907
Noshahr	4704
Bandar Mahshahr	6734
Abadan	6747
Bushehr	7051
Bandar Abbas	7137
Kish (Isl.)	7181
Bandar Lengeh	7228
Syree (Isl.)	7232
Abu-Musa (Isl.)	7240
Jask	7277
Chabahar	7257

5. CONCLUSIONS

Model calculations were carried out using several radiation models for the estimation of monthly mean global solar radiation at coastal cities. The results indicate that most of the selected models overestimated the radiation for the locations of interest. The overestimation was higher for the humid regions north (coasts), mainly due to higher relative humidity. Though replacing the new solar constant in models did not lead to an improvement of the results, other modifications (surface albedo and relative humidity) improved the model results by up to 5%. It was demonstrated that the revised Daneshyar (MD) method is able to estimate the global solar radiation in both hot arid climate (South) and humid climate (North) of the coastal regions with a reasonable accuracy (better than 7%). The prediction made by MD method (12) showed good agreement with the long-term solar measurements. For long-term (climatological) prediction of solar radiation, if cloud data (i.e., CF) are not available, using the relative sunshine hours $(1 - n/N)$ can be a reliable alternative. The predicted daily and monthly solar energy can be applied for many engineering applications at coastal regions with BWh, BSh, and Cfa climate types. Calibration of coefficients presented in diffuse formula (e.g., (7)) with the long-term diffuse experimental data (DSR) at each solar station may improve the model results. The calibration of diffuse formula merits further investigation.

ACKNOWLEDGMENTS

The author wishes to thank the Iranian Meteorological Office (IRIMO) and University of Bu-Ali Sina for their support. The author would also like to express his gratitude to the IRIMO Data Centre for providing the requisite data. This work was funded by the IRIMO Research Department as a part of a National Research Project. The author wishes to thank the anonymous reviewers and *Dr. Ann Webb* from School of Earth, Atmospheric, and Environmental Sciences, University of Manchester (UK) for their useful comments before publishing the article.

NOMENCLATURE

CF:	cloud fraction (varies from zero for clear sky to 1 for overcast sky)
D:	Daneshyar method
DA:	day angle (Radians)
DN:	day number in Julian calendar (i.e., 1 for first of January)
DSR:	diffuse solar radiation observed at solar sites
I_{dif}:	hourly diffuse radiation ($\text{cal} \cdot \text{cm}^{-2} \cdot \text{hr}^{-1}$)
I_{dir}:	hourly direct radiation ($\text{cal} \cdot \text{cm}^{-2} \cdot \text{hr}^{-1}$)
K:	geographical factor described in [1]
K_{saf}:	surface albedo factor
L:	latitude of the location (Radians)
MABE:	mean absolute bias error
MBE:	mean bias error
MD:	modified Daneshyar method
MP:	modified Paltridge method
MPE:	mean percentage error (%)
MS:	Modified Sabbagh method
N:	monthly average of daily maximum possible sunshine duration (hour)
N:	monthly average of daily sunshine duration (hour)
P:	Paltridge method
R_{dif}:	total daily diffuse radiation ($\text{cal} \cdot \text{cm}^{-2} \cdot \text{day}^{-1}$)
R_{dir}:	total daily direct radiation ($\text{cal} \cdot \text{cm}^{-2} \cdot \text{day}^{-1}$)
R_{ext}:	monthly average of extraterrestrial daily solar radiation
R_{sc}:	calculated total daily global radiation on horizontal surface ($\text{cal} \cdot \text{cm}^{-2} \cdot \text{day}^{-1}$)
$R_{\text{sc}}(\overline{\alpha}_m)$:	total daily global radiation calculated with monthly mean surface albedo of $(\overline{\alpha}_m)$
$R_{\text{sc}}(\alpha_{0.2})$:	total daily global radiation calculated with surface albedo of 0.2
RH:	relative humidity (%); measured by sheltered psychrometers
RMSE:	root mean square error
S:	Sabbagh method
SC:	solar constant
$T_{\max}$:	monthly average of maximum air temperature (C)
TSR:	total solar radiation observed at solar sites
ω_s:	sunshine hour angle (degrees)
α:	surface albedo
$\overline{\alpha}_m$:	monthly average surface albedo
δ:	solar declination angle (degrees)
θ:	solar Zenith angle (degrees)
ϕ:	latitude of the location (degrees)
$\in$:	Sun-Earth distance correction factor

REFERENCES

[1] S. J. Reddy, "An empirical method for the estimation of total solar radiation," *Solar Energy*, vol. 13, no. 2, pp. 289–290, 1971.

[2] J. A. Sabbagh, A. A. M. Sayigh, and E. M. A. Al-Salam, "Estimation of the total solar radiation from meteorological data," *Solar Energy*, vol. 19, no. 3, pp. 307–311, 1977.

[3] G. W. Paltridge and D. Proctor, "Monthly mean solar radiation statistics for Australia," *Solar Energy*, vol. 18, no. 3, pp. 235–243, 1976.

[4] M. Daneshyar, "Solar radiation statistics for Iran," *Solar Energy*, vol. 21, no. 4, pp. 345–349, 1978.

[5] K. Jafarpur and M. A. Yaghoubi, "Solar radiation for Shiraz, Iran," *Solar & Wind Technology*, vol. 6, no. 2, pp. 177–179, 1989.

[6] J. Samimi, "Estimation of height-dependent solar irradiation and application to the solar climate of Iran," *Solar Energy*, vol. 52, no. 5, pp. 401–409, 1994.

[7] A. B. Meinel and M. P. Meinel, *Applied Solar Energy*, Addison Wesly, New York, NY, USA, 1977.

[8] M. A. Yaghoubi and A. Sabazevari, "Further data on solar radiation in Shiraz, Iran," *Renewable Energy*, vol. 7, no. 4, pp. 393–399, 1996.

[9] Sh. Rehman, "Solar radiation over Saudi Arabia and comparisons with empirical models," *Energy*, vol. 23, no. 12, pp. 1077–1082, 1998.

[10] A. Al-Mohammad, "Global, direct and diffuse solar-radiation in Syria," *Applied Energy*, vol. 79, no. 2, pp. 191–200, 2004.

[11] J. Almorox, M. Benito, and C. Hontoria, "Estimation of monthly Angström-Prescott equation coefficients from measured daily data in Toledo, Spain," *Renewable Energy*, vol. 30, no. 6, pp. 931–936, 2005.

[12] J. Zhou, W. Yezheng, and Y. Gang, "General formula for estimation of monthly average daily global solar radiation in China," *Energy Conversion and Management*, vol. 46, no. 2, pp. 257–268, 2005.

[13] C. D. Ahrens, *Essential of Meteorology, An Introduction to the Atmosphere*, Wadsworth, New York, NY, USA, 2nd edition, 1998.

[14] IRIMO. Islamic Republic of Iran Meteorological Office, Data Center, Tehran, Iran; 1988–2000.

[15] P. I. Cooper, "The absorption of radiation in solar stills," *Solar Energy*, vol. 12, no. 3, pp. 333–346, 1969.

[16] M. Iqbal, *An Introduction to Solar Radiation*, Academic Press, London, UK, 1993.

[17] Royal Meteorological Institute of Belgium. Department of Aerology; 2004: http://remotesensing.Oma.be/Radiometry-Papers.

[18] J. W. Spencer, "Fourier series representation of the position of the sun," *Search*, vol. 2, p. 172, 1971.

[19] A. A. Sabziparvar, K. P. Shine, and P. M. de F. Forster, "A model-derived global climatology of UV irradiation at the earth's surface," *Journal of Photochemistry & Photobiology*, vol. 69, no. 2, pp. 193–202, 1999.