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ESTIMATION OF HEIGHT-DEPENDENT SOLAR IRRADIATION AND APPLICATION TO THE SOLAR CLIMATE OF IRAN

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Abstract—An explicitly height-dependent model has been used to estimate the solar irradiation over Iran which has a vast range of altitudes. The parameters of the model have been chosen on general grounds and not by parameters best fitting to any of the available measured irradiation data in Iran. The estimated global solar irradiation on the horizontal surface shows a very good agreement (4.1% deviation) with the 17-year long pyranometric measurements in Tehran, and also, is in good agreement with other, shorter available measured data. The entire data base of the Iranian meteorological stations have been used to establish a simple relation between the sunshine duration records and the cloud cover reports which can be utilized in solar energy estimations for sites with no sunshine duration recorders.

Clear sky maps of Iran for direct solar irradiation on tracking, horizontal, and south-facing vertical planes are presented. The global solar irradiation map for horizontal surface with cloudiness is zoned into four irradiation zones. In about four-fifths of the land in Iran, the annual-mean daily global solar irradiation on horizontal surface ranges from 4.5 to 5.4 kWh/m^2.

1. INTRODUCTION

A fairly accurate knowledge of solar radiation is needed not only in any utilization of solar energy, in particular in large scale projects, but also in meteorological and global energy-balance studies. The true mean solar irradiation over any area is, doubtless, obtained by accurate irradiation measurements over long periods of time at closely spaced stations. However, not all meteorological stations, even in industrialized countries, are equipped with pyranometers or other equipment for measuring solar irradiation. Such measurements are sparsely done in the rest of the world. Furthermore, these measurements sometimes have rather high uncertainties due to the malfunctioning or miscalibration of the instruments as has been noted by Steward *et al.* (1985), Sayigh (1987), and Moriarty (1991). Many of the problems with the measurements of solar radiation are discussed in the review article of Steward *et al.* (1985). Hence, various methods have been used to estimate the solar irradiation using the commonly available geographical and climatological data for locations where reliable measured solar irradiation data are not available.

In the most common method used for the estimation of the monthly-mean daily global solar irradiation on a horizontal surface ($\bar{H}_t$), an empirical linear relation between the ratio of $\bar{H}_t$ to the monthly mean daily extraterrestrial solar irradiation on a horizontal surface ($\bar{H}_0$) and the monthly mean daily relative sunshine duration ($\bar{s}$) is employed. The coefficients of this linear relation (the Angstrom coefficients) are usually adapted from a location with a similar climate to that which the coefficients have previously been determined by fitting the measured irradiations into the linear relation. However, the Angstrom coefficients may depend on various parameters, making the simple adaptation of the coefficients of one location to another difficult. The dependence of Angstrom coefficients on various parameters have been reviewed by Akinoglu (1991). In particular, the Angstrom linear relation does not explicitly show the dependence of the solar irradiation on altitude which is a dependence easily experienced everytime we hike. Neuwirth (1980) has related the Angstrom coefficients for Austria to altitude above sea level by a quadratic regression.

Iran not only has a variety of climates, but its terrain has a vast range of altitudes ranging from below sea level in the Caspian coastal area, to the low lands along the Persian Gulf, and to the over 1.5 km high terrain in the western and central areas. Some cities are even over 2 km above sea level. Therefore, in this work we have employed a method of estimation which explicitly incorporates the height dependence. Limited area studies of the solar radiation in Iran have been previously reported by Daneshyar (1978), Samimi (1985), and Yaghubi and Jafarpur (1990). However, in this study the complete meteorological data base available at the Iranian Meteorological Organization has been used to obtain the solar energy maps for Iran.

2. METHOD OF ESTIMATION

2.1 *Direct irradiance*

Meinel and Meinel (1977) have fitted the direct solar radiation data of Laue (1970) into an air-mass dependent exponential function with an altitude dependence. We have modified their equation slightly by including two extra factors. One factor is to account for the earth–sun distance variations, and the second factor is discussed below. The modified equation used in our estimations is

$$I_b = I_0 K_d \{(1 - ah)\exp[-b(\sec z)^c] + ahf\}. \quad (1)$$

Here I_b is the direct beam solar irradiance, z is the sun's *zenith angle*, h is the altitude of the site, I_0 is the "solar constant"; and a, b, and c are the three fitted parameters of the original Meinel-Meinel equation. The factor K_d is the inverse square of the relative earth–sun distance. It is noted that the Meinel-Meinel equation [Eqn (1) without the added factors K_d and f] gives a non-vanishing residual irradiance of I_0ah at sunrise and sunset. In order to correct for this, which otherwise would give an overestimation of the integrated daily irradiation, we have introduced the factor f. This factor was chosen to vanish at sunset and sunrise ($z = \pi/2$), and to approach unity fast at other times. Thus, the following function was tried,

$$f = 1 - \exp\left[-\frac{36}{\pi}(\pi/2 - z)\right], \qquad (2)$$

which gives $.95 < f < 1$ for sun's altitudes greater than 15°. The values of the fitted parameters as adopted from Meinel-Meinel equation are,

$$a = 0.14/\mathrm{km}, \quad b = 0.357, \quad c = 0.678. \qquad (3)$$

In this work we have used a recent figure of 1.365 kW/m^2 for the "solar constant" measured by the ERBS satellite, Ramanathar *et al.* (1989). The solar zenith angles have also been rather accurately computed using the earth's orbital and other astronomical parameters instead of approximate equations for the declination of the sun.

2.2 *Monthly-mean daily global horizontal irradiation with cloudiness*

The daily global solar irradiation on a horizontal surface is the sum of the daily beam horizontal irradiation H_b, obtained by integrating $I_b \cos z$ from sunrise to sunset, and the daily diffuse irradiation, H_d. The diffuse irradiation not only depends on cloudiness, but it also may depend on various other parameters [Moriarty (1990)]. Here, assuming an approximate linear dependence of $\bar{H}_d$ on $\bar{H}_b$, we have used a simple step function for the monthly mean daily diffuse irradiation using two approximate values for the totally clear days and the totally cloudy days:

$$(\bar{H}_d)_s = 0.1\bar{H}_b, \quad \text{totally clear days}, \qquad (4a)$$

$$(\bar{H}_d)_c = 0.3\bar{H}_b, \quad \text{totally cloudy days}. \qquad (4b)$$

It should be pointed out that $\bar{H}_b$ in Eqn (4b) is the beam horizontal daily irradiation that would be observed if the totally cloudy day was totally clear. The numerical coefficients in Eqn (4) are in the range of the mean values one obtains from the diffuse fraction correlations developed by Reindl *et al.* (1990) based on measurements in the U.S. and Europe, they are also consistent with results obtained in various other observations, Mosalam *et al.* (1990) and Nagaraja Rao *et al.* (1984). It should be remarked that the correlations of Reindl *et al.* are based on hourly data. In order to test the empirical daily coefficients of Eqn (4) using these hourly-based correlation parameters, we have used the mean daily values of these parameters along with the $\bar{H}_b/\bar{H}_0$ ratio which ranges between 0.48 to 0.64 for Iran, as computed from Eqn (1).

The sunshine duration data was also interpreted in the sense of a two-state function. In other words, if $\bar{s}$ is the monthly mean daily relative sunshine duration, then the sky was assumed to be totally clear on a fraction, $\bar{s}$, of the days in that month and totally cloudy on the remaining $(1 - \bar{s})$ fraction. Thus, for the monthly-mean daily global irradiation on horizontal surface, $\bar{H}_t$, with a monthly-mean daily relative sunshine duration of $\bar{s}$, we have

$$\bar{H}_t = \bar{s}[\bar{H}_b + (\bar{H}_d)_s] + (1 - \bar{s})(\bar{H}_d)_c. \qquad (5)$$

2.3 *The appropriate averaging periods: The solar calender*

As the averaging periods we have used the months of the "solar calender," which is the most appropriate calender for solar energy studies. In the solar calender (which is the official calender in Iran), the first day of the first month of the year coincides with the vernal equinox, and the first day of the seventh month with the autumnal equinox. Furthermore, the number of the days in the twelve months of the solar calender are chosen such that the first days of the fourth and the tenth months coincide with the solistices. Thus, the number of the days in the twelve months of the year beginning at vernal equinox are 31, 31, 31, 31, 31, 31, 30, 30, 30, 30, 30, 29 (30 on a leap year), respectively.

3. RESULTS

3.1 *Validity of the estimation method*

In order to test the validity of the above estimation method, we have to compare the results with pyranometric measurements. Such measurements have been carried out in the Tehran meteorological station for the past 17 years. Similar measurements have begun in several other cities in Iran in recent years, but the data base is not large enough for statistically meaningful averaging. (The sunshine duration records for most major cities in Iran span more than 25 years.) Thus, the comparison of the estimated with measured irradiations is only done for the Tehran station, which is shown in Fig. 1, and with a much smaller measured data base for Isfahan and Shiraz, shown in Figs. 2 and 3, respectively. The measured data has been corrected only for the very obvious errors (e.g., erroneous spikes) and the error bars shown for Tehran data are only the statistical deviations in the mean of the measured irradiations. The Isfahan data spans a period of 4 years, and that of Shiraz, only 1 year. The months of the solar calender begin at the vernal equinox. As has also been noted by Hay (1979), the Campbell-Stockes type sunshine recorders require a threshold energy for burning the paper. Thus, the true relative sunshine durations are slightly higher than what one gets from the recorded data. We have used a threshold of 50 W/m^2 on direct solar irradiance to limit the length of the effective day in computing the relative sunshine du-

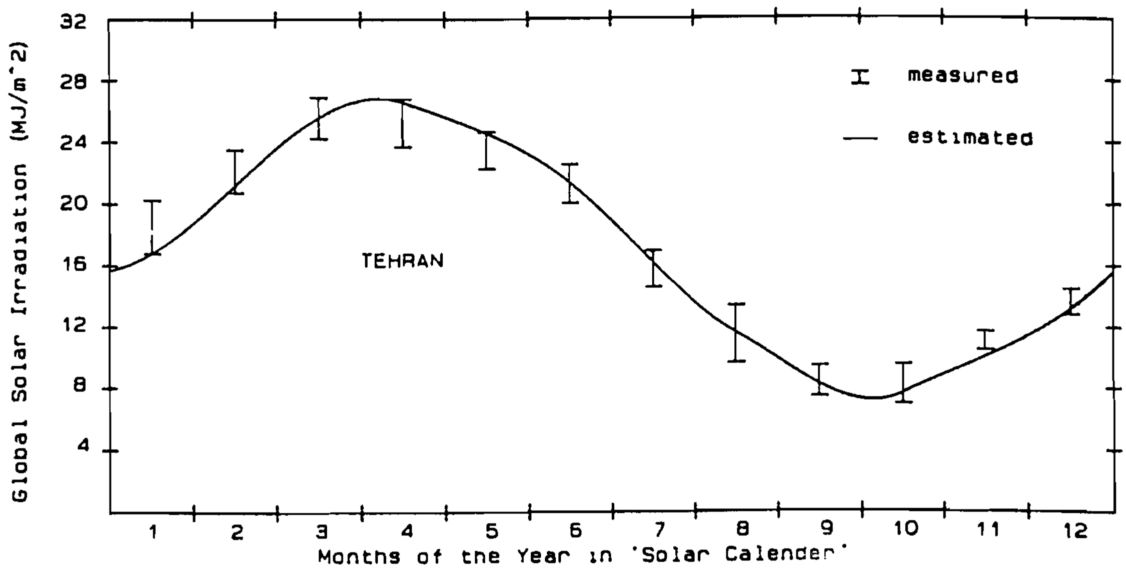

Fig. 1. Comparison of the estimated with measured monthly-mean daily global irradiation on a horizontal surface for Tehran.

ration. This threshold was estimated at the 5% level of the peak irradiance.

The root-mean-square error defined as

$$RMSE = \{[\sum_{i=1}^{12} [(\bar{H}_t)_{i,calc} - (\bar{H}_t)_{i,meas}]^2]/12\}^{1/2}, \quad (6)$$

the mean-bias error defined as

$$MBE = [\sum_{i=1}^{12} [(\bar{H}_t)_{i,calc} - (\bar{H}_t)_{i,meas}]]/12, \quad (7)$$

and the mean-absolute percentage deviation defined as

$$MADEV = 100 \times [\sum_{i=1}^{12} |[(\bar{H}_t)_{i,calc} - (\bar{H}_t)_{i,meas}]|/(\bar{H}_t)_{i,meas}]/12, \quad (8)$$

have been computed from the results presented in Figs. 1–3, and are given in Table 1. It is noted that the values of these mean errors are in the range of the corresponding values quoted by Akinoglu (1991) and by Ma and Iqbal (1984).

The *RMSE*, *MBE*, and *MADEV* for Isfahan and Shiraz are all higher than for Tehran which mainly reflect the low statistics of the measured data for these cities. It has to be emphysized that none of the parameters used in our estimation have been fitted to any of

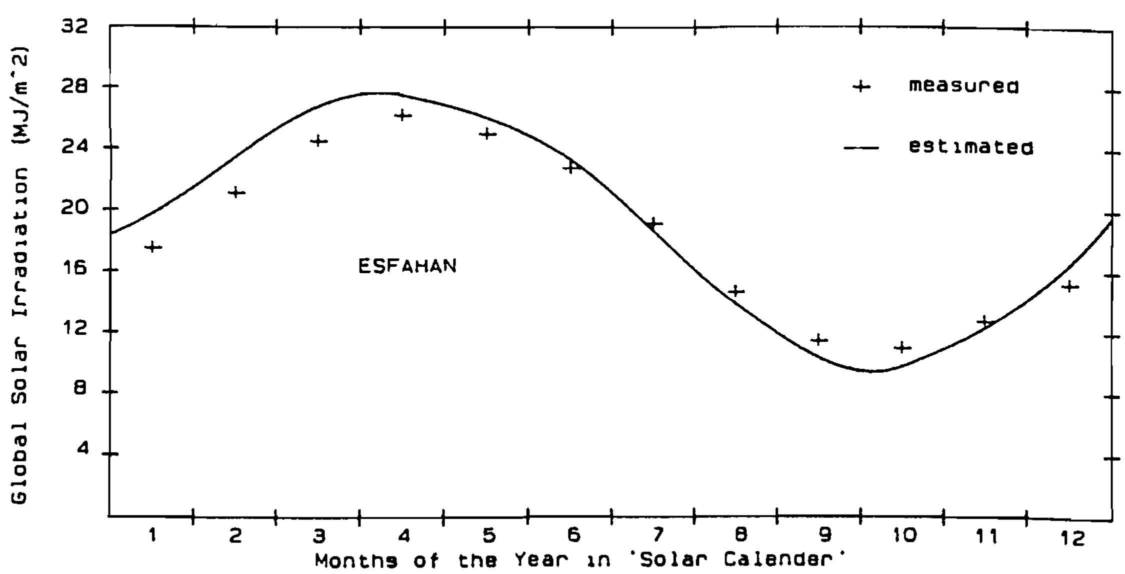

Fig. 2. Comparison of the estimated with measured monthly-mean daily global irradiation on a horizontal surface for Isfahan.

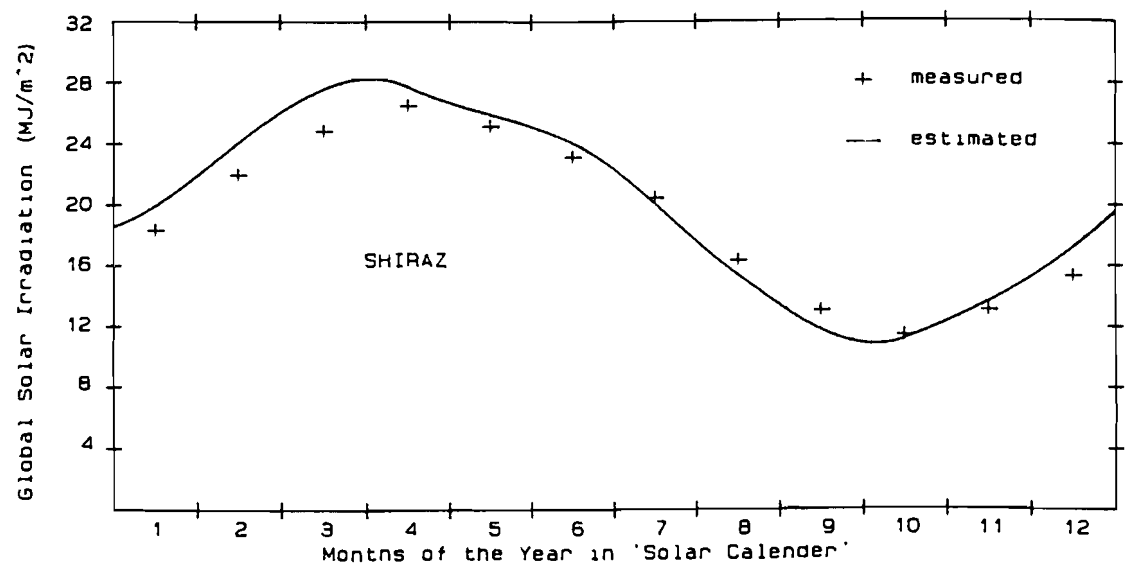

Fig. 3. Comparison of the estimated with measured monthly-mean daily global irradiation on a horizontal surface for Shiraz.

the measured irradiations. They have been chosen on general grounds as discussed above. Fitting the parameters to Tehran's measured data would still lower the values of *RMSE*, *MBE*, and *MADEV* for Tehran but not necessarily for other cities. Since this no-parameter fitting method of estimation, which explicitly contains the three main factors (latitude, altitude, and relative sunshine duration or cloud factor), has yielded quite satisfactory results (4.1% absolute mean deviation for Tehran which has a large data base), we feel confident that it could satisfactorily be used for any other location.

The relative sunshine duration data has also been correlated with the cloud cover reports of the meteorological stations. The cloud cover is reported in oktas; for each month the number of days with 0 to $\frac{2}{8}$, $\frac{3}{8}$ to $\frac{6}{8}$ and $\frac{7}{8}$ to $\frac{8}{8}$ cloud cover is reported. We have used the monthly means of these numbers to compute a monthly mean cloud factor ($\bar{c}$), assuming a linear relation within each of the three oktal ranges. Thus, we have used

$$\bar{c} = [\tfrac{1}{3}(0 + \tfrac{1}{8} + \tfrac{2}{8})n_{0-2} + \tfrac{1}{4}(\tfrac{3}{8} + \tfrac{4}{8} + \tfrac{5}{8} + \tfrac{6}{8})n_{3-6} + \tfrac{1}{2}(\tfrac{7}{8} + \tfrac{8}{8})n_{7-8}]/(n_{0-2} + n_{3-6} + n_{7-8}), \quad (9)$$

where n_{0-2}, n_{3-6}, and n_{7-8} are the monthly-mean number of days with 0 to $\frac{2}{8}$, $\frac{3}{8}$ to $\frac{6}{8}$, and $\frac{7}{8}$ to $\frac{8}{8}$ cloud cover. In a total of forty-three major meteorological stations in Iran sunshine duration records and cloud cover reports for more than 15 years exist. For these, the composite scatter plot showing the monthly mean relative sunshine duration ($\bar{s}$) versus the monthly-mean cloud factor ($\bar{c}$) is shown in Fig. 4. The scatter plot shows a very good fit to the expected simple relation of the form

$$\bar{s} = 1 - \bar{c}. \quad (10)$$

This simple relation was used to replace $\bar{s}$ in Eqn (5) by the average of $\bar{s}$ and $(1 - \bar{c})$, i.e., by $\frac{1}{2}(\bar{s} + 1 - \bar{c})$; and the calculations were repeated for Tehran. The result showed no significant change. It is to be noted that the simple relation in Eqn (10) obtained from Fig. 4 would have not resulted if correct averaging [Eqn (9)] had not been used for $\bar{c}$. A chi-square test revealed that varying the coefficients used in Eqn (9) would not better the fit or reduce the scatter in Fig. 4. Thus, the numerical coefficients used in Eqn (9), which assumes a linear relation within each of the three oktal ranges, turned out to be the best fitted coefficients for computing the cloud factor from the cloud cover data. Once the existence of the simple relation in Eqn (10) is realized, correlating the solar irradiation data separately with relative sunshine duration, as well as with cloud cover, as attempted by Tasdemiroglu and Sever (1991), seems to be redundant. Furthermore, Eqn (10) shows that for sites with no sunshine duration records, the properly averaged cloud cover reports could safely be used in solar irradiation estimations.

Table 1. The root-mean-square error (*RMSE*), the mean-bias error (*MBE*), and the mean-absolute percentage deviation (*MADEV*) in the estimation of the monthly-mean global solar irradiations

City	*RMSE* (MJ/m²)	*MBE* (MJ/m²)	*MADEV* (%)
Tehran	0.85	−0.2	4.1
Esfahan	1.46	0.6	7.0
Shiraz	1.46	0.8	6.3

3.2 *Clear-sky solar irradiation maps*

The daily direct solar irradiation for all meteorological sites in Iran (total of 350 sites) has been cal-

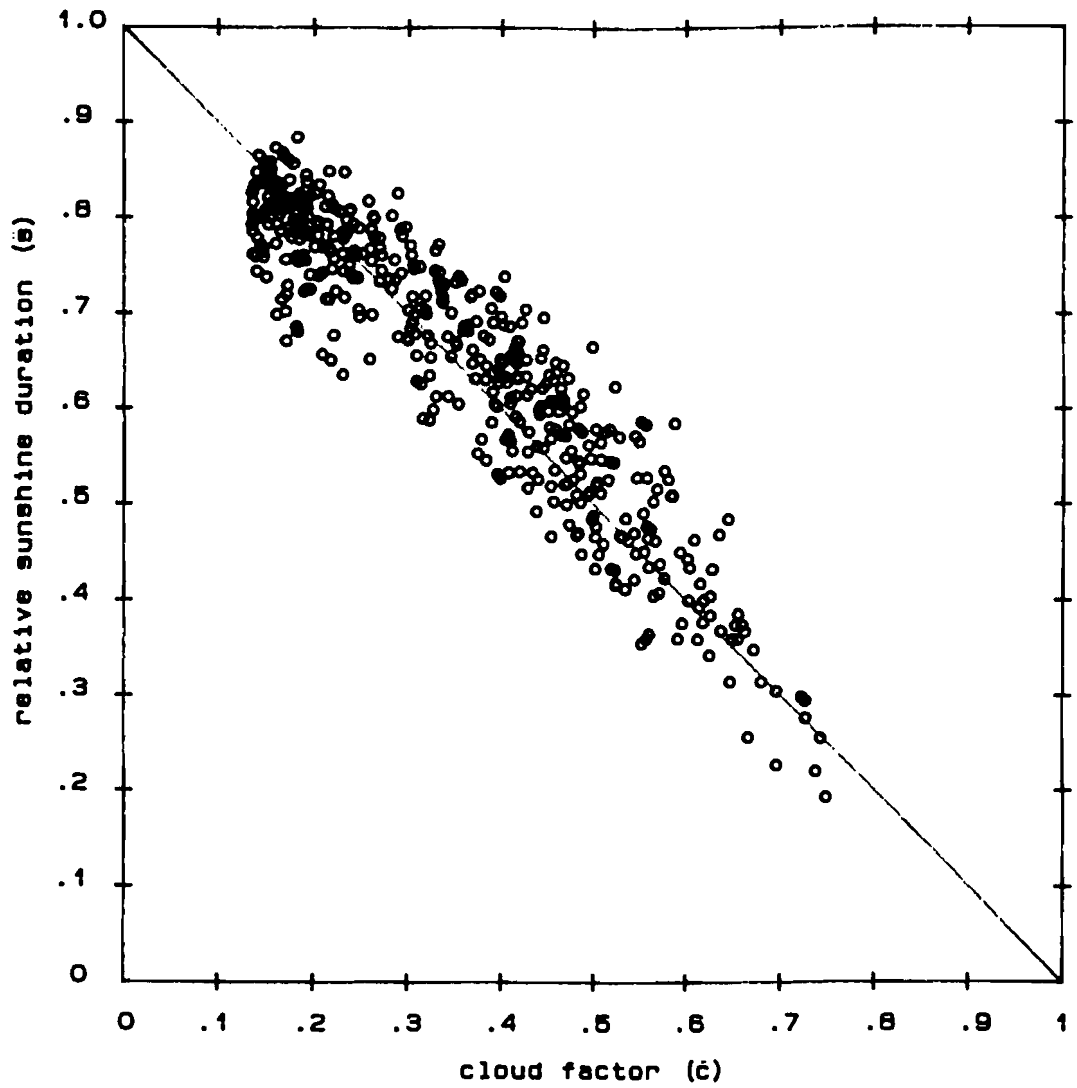

Fig. 4. Scatter plot showing the correlation of the relative sunshine duration with the cloud factor.

culated for tracking, horizontal, and south-facing vertical planes. For the titled planes, a simple isotropic approximation was used for the diffuse irradiance. The results are presented in the form of clear-sky solar irradiation maps of Iran in Figs. 5–7 for the first days of winter, spring, and summer, and for each of the three planes separately. The maps for the first day of autumn are identical to those of the first day of spring. In each map the country is divided into three solar irradiation zones. Except for the case of vertical planes, the high-latitude low lands along the Caspian Coast are in the lowest irradiation zone, and the central highlands in the highest irradiation zone. The sites whose irradiation are in a higher zone than the surrounding areas are located in exceptionally high lands. The map of the first day of winter for horizontal plane (Fig. 5) shows the most regular southward zoning with increasing irradiation, with Khuzestan (the extreme southwest province) falling in the medium rather than the high irradiation zone, due to its low altitudes. The zoning of the maps for the south-facing vertical plane is, in general, reversed with the irradiation increasing towards north, which is best seen on the first day of summer.

The clear-sky direct solar beam irradiation on tracking plane ranges from 5.1 kWh/m^2 for the lowest irradiation zone in winter to 13.3 kWh/m^2 for the highest zone in summer. That for the horizontal plane ranges from 1.7 to 8.7 kWh/m^2. For the vertical plane, the time order is reversed; the minimum of 0.1 kWh/m^2 is on the first day of summer and the maximum of 6.3 kWh/m^2 on the first day of winter.

3.3 *Global solar irradiation map with cloudiness*

A total of 43 major meteorological stations in Iran have sunshine duration records and cloud cover reports for periods longer than about 15 years (mostly longer than 25 years). For all of these, the monthly mean daily global solar irradiation on horizontal surface has been calculated. The month-to-month variation of the monthly-mean daily irradiations for different stations are all rather similar to those shown in Figs. 1–3. It is

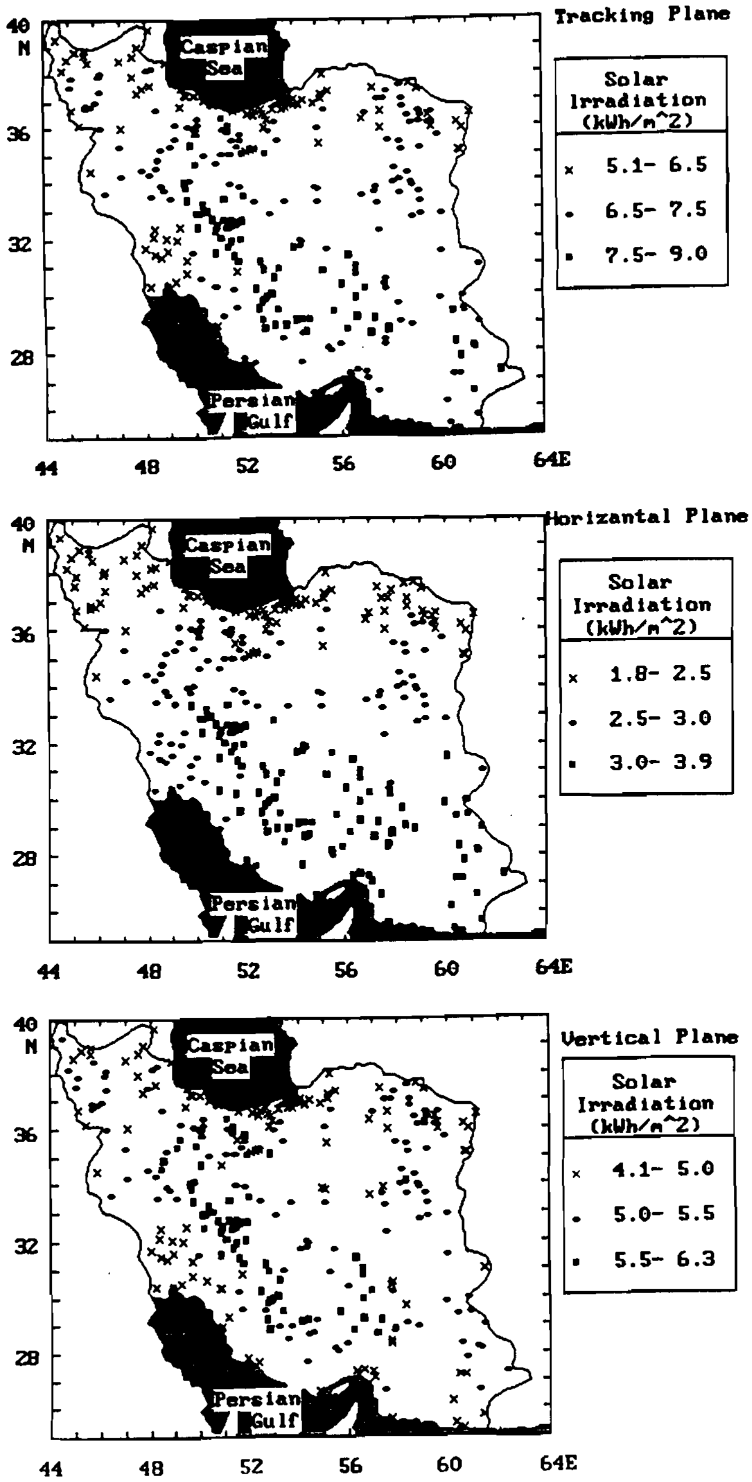

Fig. 5. Clear sky direct solar irradiation maps of Iran, first day of winter.

also noted when these irradiations, for each month are plotted on the map, the irradiation zonings of the 12 monthly maps are rather similar. Thus, here we only present the map for the annual-mean daily global solar irradiation on horizontal surface in Fig. 8. On this map, Iran has been zoned into four solar irradiation zones. The lowest zone with an annual-mean daily irradiation of 2.8 to 3.8 kWh/m^2 is the low lands of the Caspian coast, and the highest zone with an irradiation of 5.2 to 5.4 kWh/m^2 is the very high lands in the southern central part of Iran. Again, Khuzestan with its rather low latitude falls in the second lowest irradiation zone due to its low heights. The eastern coastal area of the Persian Gulf which has the lowest latitudes in Iran, due to its low height and its summer cloud cover, falls in the same zone with Tehran.

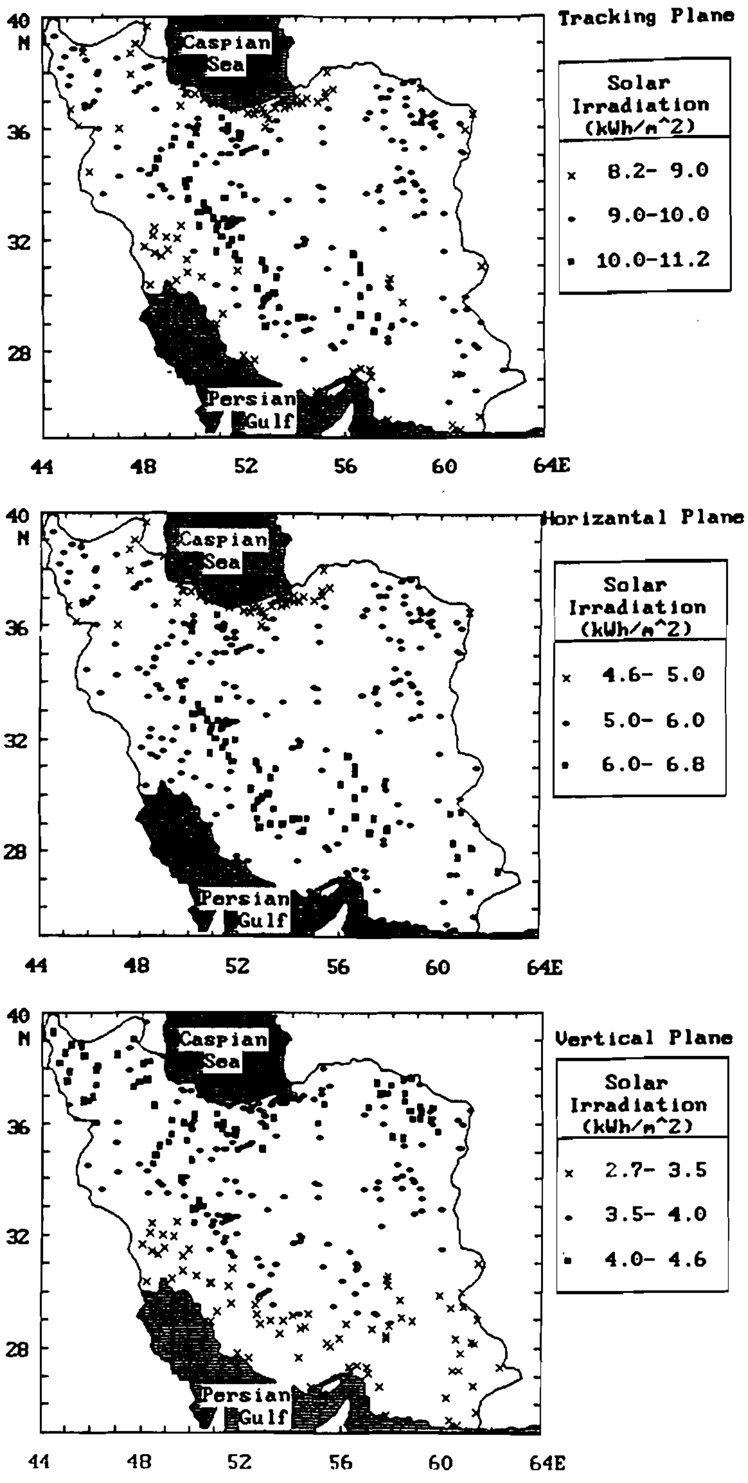

Fig. 6. Clear sky direct solar irradiation maps of Iran, first day of spring.

4. CONCLUSIONS

The explicitly height-dependent model used for the estimation of the direct solar irradiance and the simple relation incorporating the sunshine duration, or equivalently the cloud cover, data for the estimation of the global solar irradiation on horizontal surface has proved to be very satisfactory. The parameters of the model were either adapted from other works or chosen on general grounds, and not by fitting them to the measured data. Yet, the results of calculations are in very good agreement with the 17-year long pyranometric measurements of Tehran, with a mean deviation of 4.1%, and also in good agreement with measured data of shorter durations of Isfahan and Shiraz.

It was demonstrated that a cloud factor, appropriately computed from the meteorological cloud cover reports, bears a simple relation with the relative sun-

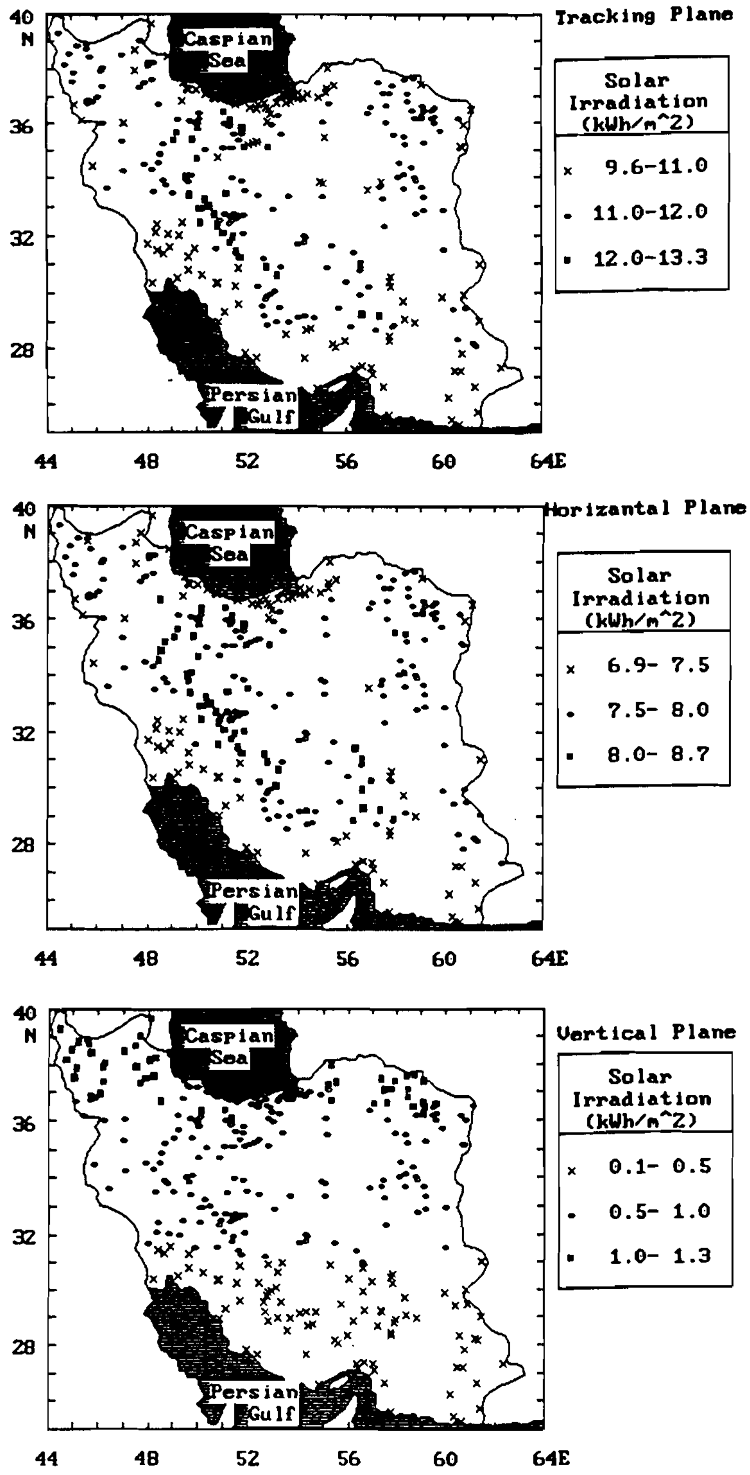

Fig. 7. Clear sky direct solar irradiation maps of Iran, first day of summer.

shine duration, as seen in Eqn (10). This relation can be used for replacing the sunshine duration data with the cloud cover data in solar irradiation estimations for sites not equipped with sunshine duration recorders. Thus, it is wise to collect cloud cover reports specially at meteorological sites not equipped with sunshine recorders (in only 43 out of 350 stations in Iran, cloud cover reports as well as sunshine duration records are available).

In the clear sky direct solar irradiation maps, Iran is zoned into three irradiation zones. The height effect, resulting in an increased solar irradiation for the mountainous high lands, can be seen on these maps. The normal latitude effect is reversed for a south-facing vertical plane which shows a general increase of solar irradiation with increasing latitude. The global solar irradiation map for horizontal surface with cloudiness is zoned into four irradiation zones. It is seen that with

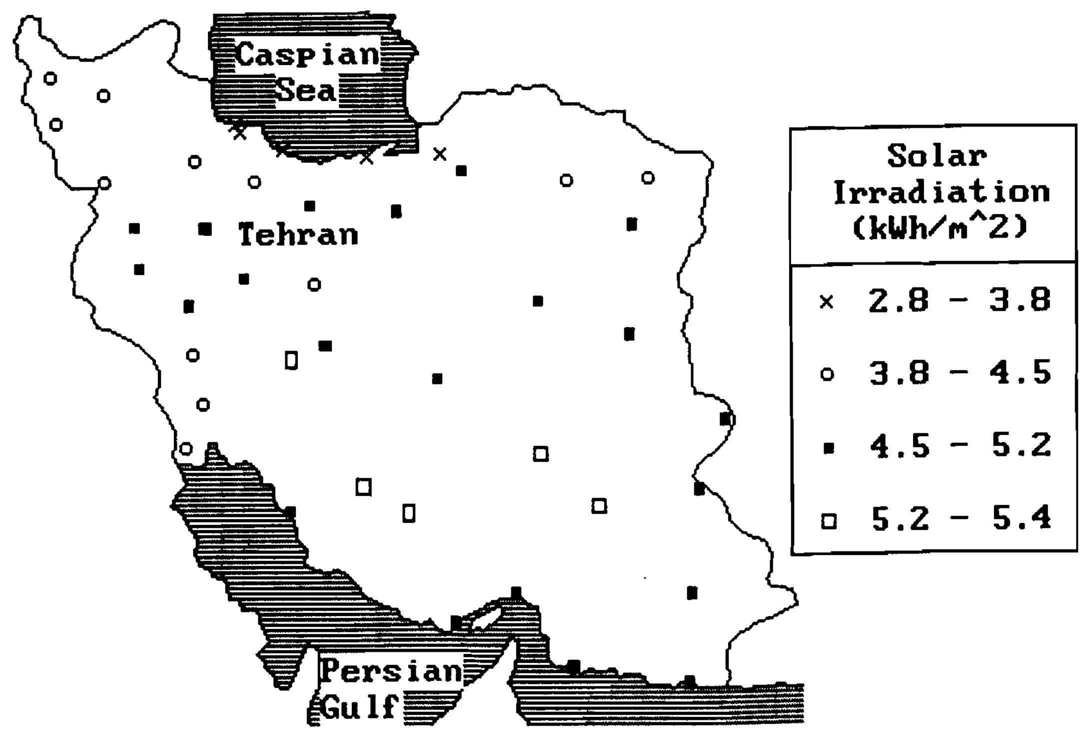

Fig. 8. Annual-mean daily global solar irradiation map of Iran with cloudiness.

about four-fifths of the land having an annual-mean daily solar irradiation ranging from 4.5 to 5.4 kWh/m^2, Iran has a very high potential for the utilization of solar energy.

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NOMENCLATURE

- c cloud factor
- I_o "solar constant"
- I_b direct solar beam irradiance on a tracking surface
- h altitude or height above sea level (in km)
- H_o extraterrestrial solar irradiation on a horizontal surface
- H_b solar beam irradiation on a horizontal surface
- H_d diffuse solar irradiation on a horizontal surface
- $(H_d)_c$ same as H_d for a totally cloudy sky
- $(H_d)_s$ same as H_d for a totally clear sky
- H_t global solar irradiation on a horizontal surface
- K_d inverse square of the relative earth–sun distance
- $MADEV$ mean-absolute percentage deviation
- MBE mean-bias error
- $RMSE$ root-mean-square error
- s relative sunshine duration (recorded daily sunshine duration divided by the length of the day)
- $\bar{x}$ monthly-mean of x
- z Sun's zenith angle

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