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Estimation of global solar radiation using clear sky radiation in Yemen

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In this communication, the usability of clear sky radiation for predicting the average global solar radiation has been investigated. For this aim, the various regression analyses were applied by using S/S_o and S/S_{nh} parameters. Also, equations which represent the two periods of the year, winter and summer, were developed by using these parameters. The equations developed by using S/S_o and S/S_{nh} have approximately the same results. Having the better values of the equations developed by using the change of summer and winter is another result. In addition, the use of the RMSE and MBE in isolation is not an adequate indicator of model performance. Using the *t*-statistic method and the harmony of results obtained with each method prove that the results are reliable.

Keywords: Clear sky radiation; Estimation of solar radiation; t-statistic.

INTRODUCTION

The solar radiation, through atmosphere, reaching the earth's surface can be classified into two components: beam radiation and diffuse radiation. Beam radiation is the solar radiation propagating along the line joining the receiving surface and the sun. It is also referred to as direct radiation. Diffuse radiation is the solar radiation scattered by aerosols, dust and molecules, it does not have a unique direction. The total radiation is the sum of the beam and diffuse radiation and is sometimes referred to as the global radiation. When the amount of diffuse radiation reaching the earth's surface is less than or equal to 25% of global radiation, the sky is termed as clear sky.

In many applications of solar energy, the solar irradiance incident on the surface of the earth at the location of interest is an important input parameter. The temporal and spatial fluctuations of such irradiance necessitate a method to predict them. The systematic variation of solar irradiance outside the earth's atmosphere makes it possible to introduce many models for such prediction (Munroe, 1980).

Knowledge of global solar radiation at a site is essential for the proper design and assessment of flat plate types solar energy conversion systems. Some of the systems such as concentrating systems require information on direct beam component whereas in the case of tilted plain surfaces the diffuse component of solar irradiance is also important for the computation of system performance (Khogali et al., 1983). However, at locations on the Earth's surface, the solar radiation is also a function of such variables as the nature and extent of cloud cover, the aerosol and water vapour content of atmosphere, etc. Good prediction of the actual value of solar irradiance for a given location requires, in principle, long-term, average meteorological data, which are still scarce for developing countries (Leung, 1980; Ezekwe and Ezeilo, 1981; Angstrom, 1924). It is, therefore, not always possible to predict the actual value of solar irradiance for a given location.

There are several formulae that relate global radiation to other climatological parameters such as sunshine hours, relative humidity, max. temperature, and average temperature. The first correlation proposed for estimating the monthly average daily global irradiation is due to Angstrom (Angstrom, 1924). The original Angstrom-type regression equation related monthly average daily radiation to clear day radiation at the location in the question and average fraction of possible sunshine hours:

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Table 1. Correction factors for climate types.

Climate type	r_o	r_1	r_k
Tropical	0.95	0.98	1.02
Mid- atitude summer	0.97	0.99	1.02
Sub- arctic summer	0.99	0.99	1.01
Mid latitude- winter	1.03	1.01	1.00

$H/H_c = a + b(S/S_o)$ (1)

A basic difficulty with Eq. (1) lies in the ambiguity of the terms S/S_o and H_c. Page (Page, 1964) and the other have modified the method to base it on extraterrestrial radiation on a horizontal surface rather than on clear sky day radiation.

$H/H_o = a' + b'(S/S_o)$ (2)

Where H_o is the extraterrestrial radiation (MJ/m^2) and a' and b' are constant depending on location. In spite of having complication of H_c calculations, the better results were obtained by using H_c instead of H_o (Togrul, 1999).

The major objective of this article is to investigate usability of clear sky radiation to predict and express the average measured values of solar irradiance on a horizontal surface by using various regression analyses in Yemen.

Estimation of clear sky radiation

Hottel (Hottel, 1976) has presented a method for estimating the beam radiation transmitted through clear atmospheres which takes into account zenith angle and altitude for a standard atmosphere and four climate types. The atmospheric transmittance for beam radiation τ_b is given in the form:

$\tau_b = a_o + a_1 \exp(-k/\cos\theta_z)$ (3)

The constant a_o, a_1 and k for the standard atmosphere with 23 km visibility are found from a_o^*, a_1^* and k^* which are given for altitudes less than 2.5 km by

$a_o^* = 0.4237 - 0.00821(6 - A)^2$ (4)

$a_1^* = 0.5055 + 0.00595(6.5 - A)^2$ (5)

$k^* = 0.2711 + 0.01858(2.5 - A)^2$ (6)

where A is the altitude of the observer in kilometers.

The correction factors are applied to a_o^*, a_1^* and k^* to allow for changes in climate types.

The correction factors $r_o = a_o/a_o^*$, $r_1 = a_1/a_1^*$ and $r_k = k/k^*$ are given in Table 1.

Thus, the transmittance of this standard atmosphere for beam radiation can be determined for any zenith angle and any altitude up to 2.5 km. The clear sky beam radiation (G_{cb}, Wm^{-2}) is than

$G_{cb} = G_{on}\tau_b$ (7)

Where G_{on} is the extraterrestrial radiation, measured on the plane normal to the radiation on the *n*th day of the year and given in the following form (W m^{-2}).

$G_{on} = G_{sc}(1 + 0.033\cos(360n/365))$ (8)

Where G_{sc} is the solar constant and is equal to 1367 W m^{-2}.

The clear sky horizontal beam radiation is:

$G_{cb} = G_{on}\tau_b\cos\theta_z$ (9)

It is also necessary to estimate the clear sky diffuse radiation on a horizontal surface to get the total radiation Liu and Jordan (Liu and Jordan, 1960) developed in an empirical relationship between the transmission coefficient for beam and diffuse radiation for clear days.

$\tau_d = 0.271 - 0.294\,\tau_b$ (10)

Where τ_d is the ratio of diffuse radiation to the extraterrestrial (beam) radiation on the horizontal plane. The clear sky diffuse radiation G_{cd} (W m^{-2})

$G_{cd} = G_{on}\tau_d\cos\theta_z$ (11)

The clear sky global solar radiation is given by:

$G_c = G_{cb} + G_{cd}$ (12)

Data

The objective of this study is to develop some statistical relations to estimate monthly mean daily global solar radiation by using clear sky radiation in Yemen. For this aim, the department of Physics of Sana'a University, the Meteorological Department of the Civil Aviation and Meteorological Authority in Sana'a installed on the roof of the Faculty of Science building a few Eppley pyranometers and a pyrheliometer comprising electronic integrators and printers for recording global, diffuse and beam solar irradiances. An actinograph and a Campbell-Stokes sunshine recorder were also installed at the same site. These instruments are often checked and calibrated to maintain an accuracy of at least 5 per cent. The maximum difference between the actinograph records and the Eppley pyranometer which registers global irradiance does not exceed 5 per cent.

Another meteorological station in Sana'a is the airport station which has been recording duration of sunshine and global solar irradiance by means of an actinography. There are meteorological stations in five other towns of Yemen (Khogali et al., 1983).

The longitude, latitude and altitude of the six cities are given in Table 2. The measured values of the monthly average global solar radiation G and the monthly average

Table 2. Geographical location of six Yemen cities

Station (State)	Longitude (ºE)	Latitude (ºN)	Altitude (m)
Sana'a	44.26	15.52	2210
El Boun	44.97	15.73	2100
Hodeidah	42.98	14.75	33
El kahber	44.83	14.38	2100
Taiz	43.95	13.58	1400
El Macha	43.28	13.25	10

Table 3. Measured values of monthly average global solar radiation (G) and S/So for six cities (khogali et al., 1983).

	Sana'a		El Boun		Hodeidah		El Khaber		Taiz		El Mecha	
Month	**G**	**S/So**	**G**	**S/So**	**G**	**S/So**	**G**	**S/So**	**G**	**S/So**	**G**	**S/So**
Jan	5.31	0.842	NA	0.7248	4.97	0.748	4.86	0.7555	5.08	0.6818	5	0.7161
Feb	5.78	0.8557	6.22	0.9214	4.91	0.7281	6	0.8745	5.72	0.7516	5.55	0.7509
Mar	5.67	0.7347	6.03	0.7893	5.97	0.6966	6.05	0.7468	5.92	0.7633	6.39	0.7128
Apr	6.19	0.7222	6.58	0.7607	6.38	0.7378	6.78	0.8357	5.81	0.7557	6.94	0.7806
May	6.08	0.7231	6.25	0.7461	6.17	0.7568	6.64	0.7894	5.89	0.7127	NA	0.7611
Jun	6.5	0.7028	6.42	0.7199	5.83	0.6532	6.25	0.7245	NA	0.6099	6.22	0.5952
Jul	5.67	0.5755	NA	0.6233	5.58	0.5477	5.44	0.5799	NA	0.5033	6.08	0.5749
Aug	5.64	0.5996	6.19	0.6392	5.3	0.5769	5.22	0.5373	NA	0.5867	5.89	0.5631
Sep	6.34	0.7449	5.89	0.7779	5.47	0.621	5.92	0.7287	NA	0.6213	5.83	0.6214
Oct	6.25	0.859	6.89	0.8766	5.78	0.7204	6.17	0.8913	5.38	0.7957	6.22	0.8123
Nov	5.45	0.865	6.17	0.888	5.17	0.8046	5.75	0.9092	5.11	0.8006	5.75	0.8697
Dec	5.19	0.858	5.47	0.8843	4.83	0.7718	5.5	0.9315	4.72	0.7848	5.22	0.819

daily hours of bright sunshine S for six locations are given in Table 3. G_c values calculated for six cities are given in Table 4. The correlations have been studied by using both the ratios S/S_o and S/S_{nh} , where S_{nh} is the monthly mean sunshine duration taking into account the natural horizon of the site, and is given in the following equation:

$$\frac{1}{S_{nh}} = \frac{0.8706}{S_o} + 0.0003 \qquad (13)$$

In this work, we developed equations to estimate monthly mean global solar radiation G, applying various regression types to parameters such as S/S_o and S/S_{nh}. The effects which the solar radiation is exposed to until it reaches to the earth from the atmosphere change a lot for winter and summer. Therefore it will be a true approach to compute the reaching monthly mean global solar radiation for both summer (April – September) and winter (October – March).

Thus the relation between $G/G_c = f\ (S/S_o)$ and $G/G_c = f\ (S/S_{nh})$ were investigated by different regression analyses for the whole year as well as for the two period of the year i.e. summer & winter.

The values of G were estimated by using these developed equations. These values were then compared with original measured values for each city.

Equations

The following equations were obtained when we investigated the relation between S/S_o and G/G_c by trying different regression types. The scatter of monthly mean values between S/S_o and G/G_c are given in Figure 1.

$G/G_c = 0.5152(S/S_o) + 0.4603$ (14)

$G/G_c = 0.9078(S/S_o)^2 - 0.8153(S/S_o) + 0.9387$ (15)

$G/G_c = 4.0401(S/S_o)^3 - 8.010(S/S_o)^2 + 5.6524(S/S_o) - 0.6001$ (16)

$G/G_c = 0.9607(S/S_o)^{0.4417}$ (17)

$G/G_c = 0.3639 \ln(S/S_o) + 0.9547$ (18)

$G/G_c = 0.5281e^{0.623(S/S_o)}$ (19)

The results of regression analyses applied for summer (April- September) are given below.

$G/G_c = 0.336(S/S_o) + 0.5737$ (20a)

$G/G_c = 0.6173(S/S_o)^2 - 0.4944(S/S_o) + 0.8485$ (21a)

$G/G_c = 27.308(S/S_o)^3 - 55.698(S/S_o)^2 + 37.874(S/S_o) - 7.7809$ (22a)

$G/G_c = 0.8969(S/S_o)^{0.2938}$ (23a)

$G/G_c = 0.2226 \ln(S/S_o) + 0.8898$ (24a)

$G/G_c = 0.5915e^{0.442(S/S_o)}$ (25a)

The results of regression analyses applied for winter

Table 4. Gc values for each city (using Hottle model) in KW/m^2/day.

Months	Sana'a	El Boun	Hodeidah	El Khaber	Taiz	El Macha
Jan	5.9753	5.9292	6.0374	6.0777	5.9604	5.2863
Feb	6.6978	6.6557	6.7395	6.7705	6.6237	5.9055
Mar	7.3992	7.3638	7.4121	7.4298	7.2465	6.4882
Apr	7.8189	7.7919	7.7991	7.8011	7.5814	6.7987
May	7.8638	7.8438	7.8188	7.8086	7.5644	6.7767
Jun	7.7908	7.7741	7.7348	7.7193	7.4657	6.6808
Jul	7.7924	7.7743	7.7414	7.7284	7.4800	6.6972
Aug	7.7943	7.7705	7.7637	7.7605	7.5319	6.7531
Sep	7.5235	7.4917	7.5236	7.5350	7.3391	6.5777
Oct	6.8813	6.8416	6.9136	6.9402	6.7831	6.0577
Nov	6.1314	6.0865	6.1881	6.2260	6.1019	5.4200
Dec	5.7404	5.6935	5.8074	5.8500	5.7411	5.0829

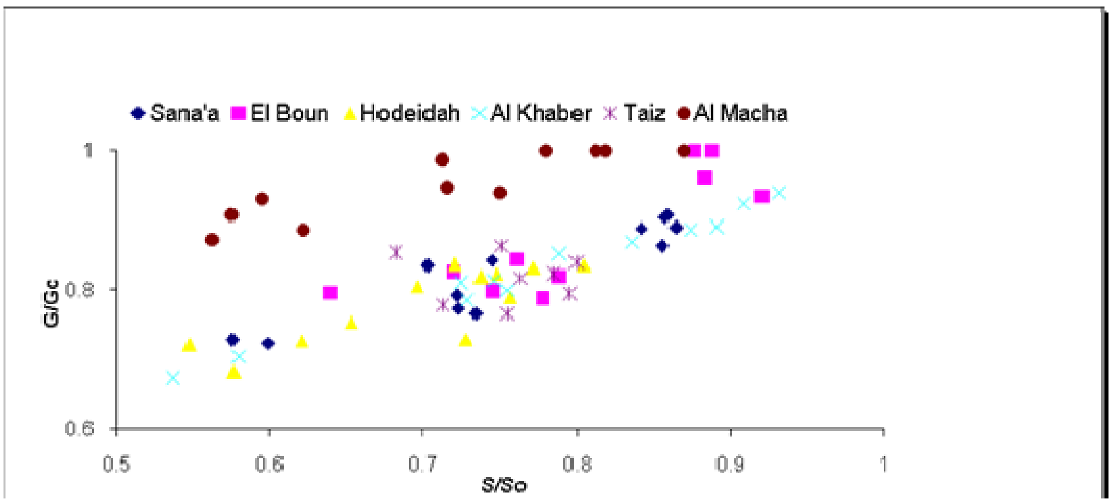

Figure 1. The variation of G/Gc vs S/So for six towns inYemen.

(October – March) are given below.

$G/G_c = 0.5524(S/S_o) + 0.4377$ (20b)

$G/G_c = 2.3437(S/S_o)^2 - 3.2345(S/S_o) + 1.9561$ (21b)

$G/G_c = -50.088(S/S_o)^3 + 123.58(S/S_o)^2 - 100.62(S/S_o) + 27.914$ (22b)

$G/G_c = 0.9829(S/S_o)^{0.505}$ (23b)

$G/G_c = 0.4387 \ln(S/S_o) + 0.9792$ (24b)

$G/G_c = 0.527e^{0.6359(S/S_o)}$ (25b)

The linear regression analyses to investigate the usability of S/S_{nh} ratio for computing the monthly mean global solar radiation were made. The results of these analyses can be seen as the following equations. The effect of S/S_{nh} on the G/G_c is given in Figure 2.

$G/G_c = 0.5899(S/S_{nh}) + 0.46$ (26)

$G/G_c = 1.189(S/S_{nh})^2 - 0.9343(S/S_{nh}) + 0.9391$ (27)

$G/G_c = 6.0901(S/S_{nh})^3 - 10.562(S/S_{nh})^2 + 6.5159(S/S_{nh}) - 0.6106$ (28)

$G/G_c = 1.0196(S/S_{nh})^{0.4421}$ (29)

$G/G_c = 0.3642 \ln(S/S_{nh}) + 1.0038$ (30)

$G/G_c = 0.5279e^{0.7132(S/S_{nh})}$ (31)

The effect of S/S_{nh} ratio on G/G_c for summer (April-September) is investigated by various regression analyses and the results are given below.

$G/G_c = 0.3844(S/S_{nh}) + 0.5737$ (32a)

$G/G_c = 0.8047(S/S_{nh})^2 - 0.562(S/S_{nh}) + 0.8475$ (33a)

$G/G_c = 40.917(S/S_{nh})^3 - 72.975(S/S_{nh})^2 + 43.391(S/S_{nh}) - 7.7962$ (34a)

$G/G_c = 0.933(S/S_{nh})^{0.2939}$ (35a)

$G/G_c = 0.2227 \ln(S/S_{nh}) + 0.9198$ (36a)

$G/G_c = 0.5915e^{0.5057(S/S_{nh})}$ (37a)

The results of various regression analyses applied for winter (October – March) are given below.

$G/G_c = 0.6323(S/S_{nh}) + 0.4375$ (32b)

$G/G_c = 3.0574(S/S_{nh})^2 - 3.6857(S/S_{nh}) + 1.9508$ (33b)

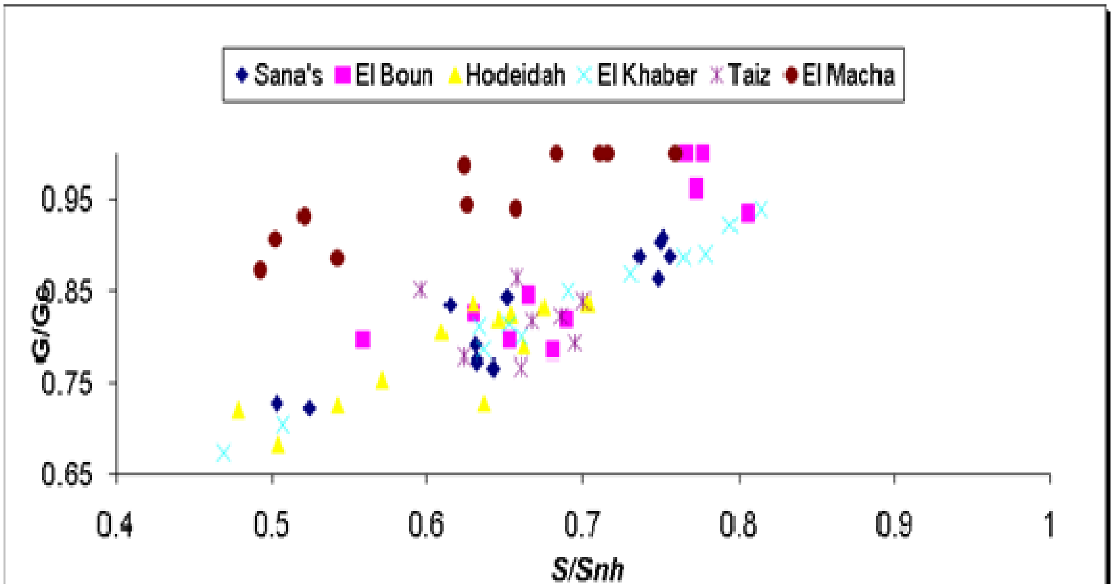

Figure 2. The variation of G/Gc vs S/Snh for six towns in Yemen.

$G/G_c = -74.908(S/S_{nh})^3 + 161.53(S/S_{nh})^2 - 114.94(S/S_{nh}) + 27.87$ (34b)

$G/G_c = 1.0522(S/S_{nh})^{0.5052}$ (35b)

$G/G_c = 0.4389 \ln(S/S_{nh}) + 1.0383$ (36b)

$G/G_c = 0.5269e^{0.7278(S/S_{nh})}$ (37b)

COMPARISON METHODS OF RESULTS

In this study, two statistical tests, root mean square error (RMSE) and mean bias error (MBE), and t-statistic were used to evaluate the accuracy of the correlations described above.

Root mean square error

The root mean square error is defined as

$$\text{RMSE} = \left(\frac{1}{N}\sum_{i=1}^{N}\left(G_{i,pre} - G_{i,meas}\right)^2\right)^{1/2} \quad (38)$$

where $G_{i,pre}$ is *i*th predicted value, $G_{i,meas}$ is the *i*th measured value, and N is the total number of observations. The RMSE is always positive, a zero value is ideal. This test provides information on short- terms performance of the correlation by arranging a term by term comparison of the actual deviation between the calculated value and the measured value. The smaller the value, the better the model's performance. However, a few large errors in the sum can produce a significant increase in RMSE.

Mean bias error

The mean bias error is defined as

$$\text{MBE} = \frac{1}{N}\sum_{i=1}^{N}\left(G_{i,pre} - G_{i,meas}\right) \quad (39)$$

This test provides information on the long term performance. A low MBE is desired. Ideally a zero value of MBE should be obtained. A positive value gives the average amount of over-estimation in the calculated value and vice versa. A drawback of this test is that over estimation of an individual observation will cancel under estimation in a separate observation.

It is obvious that each test by itself may not be an adequate indicator of a model's performance. It is possible to have a large RMSE value and at the same time a small MBE (a large scatter about the line of perfect estimation). On the other hand, it is also possible to have a relatively small RMSE and a relatively large MBE (a consistently small over – or under – estimation).

However although these statistical indicators generally provide a reasonable procedure to compare models, they do not objectively indicate whether a model's estimates are statistically significant, i.e. , not significantly different from their measured counterparts. In this article an additional statistical indicator, the *t*-statistic was used. This statistical indicator allows models to be compared and at the same time indicate whether or not a model's estimates are statistically significant at a particular confidence level (Stone, 1993). It was seen that the *t*-statistic used in addition to the RMSE and MBE gave more reliable and explanatory results (Togrul, 1998).

Derivation of the t-statistic from the RMSE and MBE

The t-statistic is defined as (Walpole and Mayers, 1989),

$$t = \frac{\frac{1}{N}\sum_{i=1}^{N} d_i}{\frac{S}{N^{1/2}}} \qquad (40)$$

where N is the numbers of data pairs, d_i is the difference between ith estimated value and ith measured value and S is the standard deviation of the difference between estimated and measured values and is given by:

$$S^2 = \frac{N\sum_{i=1}^{N} d_i - \left(\sum_{i=1}^{N} d_i\right)^2}{N(N-1)} \qquad (41)$$

Rearranging the equations (25) and (26) gives;

$$\sum_{i=1}^{N} d_i^2 = N\,(\text{RMSE})^2 \qquad (42)$$

$$\sum_{i=1}^{N} d_i = N\,(\text{MBE}) \qquad (43)$$

Combining Eqs. (40) and (43) yields;

$$t = \frac{MBE}{\frac{S}{N^{1/2}}} \qquad (44)$$

Using the equations (42) and (43) in conjunction with Eq. (41) gives:

$$S = \left(\frac{N(RMSE^2 - MBE^2)}{N-1}\right)^{1/2} \qquad (45)$$

Substituting for S in equation (40) yields:

$$t = \left[\frac{(N-1)MBE^2}{RMSE^2 - MBE^2}\right]^{1/2} \qquad (46)$$

The smaller the value of t, the better is the model's performance. To determine whether a model's estimates are statistically significant, one simply has to determine a critical t value obtainable from standard statistical tables, at a particular confidence level, i.e. $t_{\alpha/2}$ at the α level of significance and (N-1) degrees of freedom. For the model's estimates to be judged statistically significant at the 1- α confidence level, the calculated t value must be less than the critical t value.

RESULTS AND DISCUSSION

If we group the developed equations which include different variables and two period of year, the comparison will be more detailed.

GROUP I [Eqs. (14)–(19)]: the developed equations which include the whole year by using S/S_o parameter.

GROUP II [Eqs. (20)–(25)]: equations for both summer and winter by using S/S_o parameter.

GROUP III [Eqs. (26)–(31)]: equations which include the whole year by using S/S_{nh} variable.

GROUP IV [Eqs. (32)–(37)]: equations for two period of year, summer and winter by using S/S_{nh} parameter.

It was shown in Table 5 that the good results were not seen in the short term but, relatively good results were seen in the long term. Eq. (17) has the best result among the equation developed in Group I. Similarly the best MBE and RMSE values were obtained by Eq. (22) in Group II.

When we compared the developed equation in Group III, the best MBE and RMSE values were seen in Eq. (29) and Eq. (28) respectively, Similarly in Group IV, the best MBE and RMSE values were seen in Eq. (33), (36) and Eq. (34) respectively. When we investigate all the equations the best MBE value was seen in Eq. (22). The best RMSE value were obtained with Eq.(22) and Eq. (34) and these equations are from Group II and Group IV.

Considering the whole country and each city, the performance of developed equations are different. Therefore, the MBE and RMSE values of the developed equations for each city were calculated. The results of the statistical comparison are given in Table 6.

At the first view, it was seen that the MBE and RMSE values of table 6 are higher than the table 5. Each equation according to the city was compared with the equations in its group. The results obtained were set up in order below.

Sana'a:- Eq (19) in Group I has the best result and in Group II, Eq. (25) has the better result. A relatively good result was obtained by Eq. (31) in Group III. In Group IV the best MBE and RMSE values were obtained by Eq. (33) and (37), and Eq. (35) and (37) respectively.

El Boun:- The best result in Group I and II, were obtained by Eq. (16), and Eq. (21) and (22), respectively. Similarly the best MBE and RMSE values in Group III and IV were obtained by Eq. (28) and Eq. (33) respectively.

Hodeidah:-In group I and II, the best values of MBE and RMSE were obtained by Eq. (19) and Eq. (25) respectively. Similarly Eq. (31) and Eq. (37) give the better result for MBE and RMSE values in Group III and IV respectively.

El Khaber:- Eq. (17) in Group I, Eq. (22) and (23) in Group II, Eq. (29) in Group III, and Eq. (35) in Group IV showed relatively good results.

Taiz:- Eq. (16) in Group I, Eq. (22) in Group II, Eq. (28) in Group III and Eq. (34) in Group IV, showed relatively better results.

El Macha:- Eq. (16) in Group I, Eq. (22) in Group II, Eq. (27) in Group III and Eq. (34) in Group IV, showed the lowest error.

Although the models give good results for the whole country (Table 5), the highest errors were obtained for cities (Table 6). These tables did not include adequate information about performance of the developed equa-

Table 5. RMSE and MBE for the equation developed for Yemen.

Equation number	RMSE	MBE
Group I		
14	0.4644	0.0115
15	0.4586	0.0106
16	0.4579	0.0147
17	0.4661	-0.0053
18	0.4698	0.0124
19	0.4612	-0.0061
Group II		
20	0.4559	0.0063
21	0.4535	0.0064
22	0.4413	-0.0011
23	0.4554	-0.0108
24	0.4570	0.0064
25	0.4544	-0.0101
Group III		
26	0.4644	0.0119
27	0.4587	0.0108
28	0.4578	0.0124
29	0.4661	-0.0056
30	0.4698	0.0127
31	0.4613	-0.0063
Group IV		
32	0.4559	0.0066
33	0.4539	0.0065
34	0.4417	0.0108
35	0.4554	-0.0107
36	0.4570	0.0065
37	0.4544	-0.0106

Table 6. The RMSE and MBE values of the equation developed for each city.

	Sana'a		El Boun		Hodeidah		El Khaber		Taiz		El Mecha	
Equation	**RMSE**	**MBE**	**RMSE**	**MBE**	**RMSE**	**MBE**	**RMSE**	**MBE**	**RMSE**	**MBE**	**RMSE**	**MBE**
Group I												
14	0.2695	0.1803	0.3758	-0.0160	0.3562	0.2875	0.2704	0.2285	0.3622	0.2361	0.8678	-0.8489
15	0.2659	0.1775	0.3323	-0.0109	0.3572	0.2722	0.3152	0.2637	0.3297	0.1867	0.8595	-0.8416
16	0.2719	0.1805	0.3304	0.0002	0.3628	0.2793	0.3075	0.2659	0.3215	0.1857	0.8587	-0.8404
17	0.2614	0.1631	0.3883	-0.0369	0.3462	0.2759	0.2511	0.2019	0.3568	0.2295	0.8832	-0.8640
18	0.2770	0.1815	0.3976	-0.0208	0.3644	0.2982	0.2635	0.2133	0.3737	0.2541	0.8686	-0.8486
19	0.2548	0.1620	0.3659	-0.0312	0.3389	0.2650	0.2593	0.2177	0.3454	0.2108	0.8827	-0.8643
Group II												
20	0.2781	0.1762	0.3029	-0.0504	0.3643	0.2924	0.2941	0.2118	0.3482	0.2732	0.8553	-0.8352
21	0.2724	0.1549	0.3016	-0.0462	0.3680	0.2962	0.3087	0.2406	0.3138	0.2563	0.8562	-0.8369
22	0.2923	0.1816	0.2635	-0.0632	0.3772	0.2814	0.2720	0.2043	0.2770	0.2231	0.8401	-0.8192
23	0.2661	0.1612	0.3043	-0.0649	0.3475	0.2729	0.2756	0.1904	0.3411	0.2613	0.8730	-0.8536
24	0.2802	0.1802	0.3035	-0.0518	0.3661	0.2940	0.2922	0.2037	0.3543	0.2777	0.8551	-0.8344
25	0.2646	0.1577	0.3042	-0.0625	0.3464	0.2720	0.2783	0.1999	0.3355	0.2571	0.8725	-0.8536
Group III												
26	0.2698	0.1807	0.3760	-0.0153	0.3564	0.2877	0.2709	0.2291	0.3625	0.2364	0.8675	-0.8487

Table 6 Cont.

27	0.2660	0.1777	0.3326	-0.0105	0.3573	0.2722	0.3155	0.2642	0.3298	0.1868	0.8593	-0.8415
28	0.2705	0.1782	0.3307	-0.0022	0.3612	0.2771	0.3056	0.2637	0.3201	0.1833	0.8606	-0.8424
29	0.2613	0.1628	0.3885	-0.0371	0.3459	0.2755	0.2510	0.2018	0.3566	0.2289	0.8835	-0.8643
30	0.2773	0.1818	0.3979	-0.0203	0.3646	0.2983	0.2639	0.2138	0.3739	0.2542	0.8683	-0.8484
31	0.2547	0.1619	0.3662	-0.0312	0.3387	0.2647	0.2593	0.2177	0.3453	0.2104	0.8829	-0.8646
Group IV												
32	0.2783	0.1765	0.3194	-0.0501	0.3648	0.2926	0.2998	0.2122	0.3359	0.2297	0.8518	-0.8260
33	0.2726	0.1551	0.3152	-0.0461	0.3683	0.2963	0.3134	0.2408	0.2917	0.2113	0.8528	-0.8285
34	0.3022	0.1935	0.2657	-0.0503	0.3855	0.2915	0.2851	0.2169	0.2715	0.2015	0.8274	-0.8026
35	0.2662	0.1614	0.3224	-0.0647	0.3476	0.2729	0.2807	0.1906	0.3302	0.2173	0.8639	-0.8439
36	0.2803	0.1804	0.3214	-0.0517	0.3665	0.2941	0.2977	0.2040	0.3435	0.2342	0.8518	-0.8252
37	0.2644	0.1572	0.3207	-0.0631	0.3462	0.2714	0.2832	0.1995	0.3225	0.2122	0.8697	-0.8446

Table 7. Critical t-values and the results of t-statistic analyses for each city.

Equation	Sana'a	El Boun	Hodeidah	El Khaber	Taiz	El Macha
Group I						
14	2.985	0.128	4.534	5.221	2.274	14.903
15	2.974	0.098	3.903	5.065	1.818	15.252
16	2.944	0.002	4.001	5.710	1.872	15.071
17	2.648	0.287	4.376	4.485	2.222	14.917
18	2.877	0.157	4.722	4.573	2.454	14.480
19	2.732	0.257	4.160	5.126	2.038	15.244
Group II						
20	2.716	0.479	4.453	3.315	2.480	12.531
21	2.292	0.445	4.496	3.973	2.781	12.989
22	2.619	0.716	3.676	3.634	2.677	12.944
23	2.525	0.616	4.201	3.067	2.310	12.668
24	2.785	0.490	4.459	3.114	2.469	13.285
25	2.462	0.597	4.199	3.306	2.313	12.899
Group III						
26	2.991	0.122	4.536	5.256	2.276	14.941
27	2.978	0.095	3.901	5.081	1.818	15.293
28	2.904	0.020	3.967	5.663	1.848	15.130
29	2.642	0.288	4.369	4.484	2.214	14.919
30	2.880	0.153	4.719	4.584	2.453	14.516
31	2.731	0.257	4.155	5.126	2.033	15.289
Group IV						
32	2.718	0.477	4.454	3.323	2.479	12.554
33	2.295	0.443	4.492	3.982	2.780	12.961
34	2.765	0.578	3.832	3.888	2.930	12.623
35	2.529	0.614	4.204	3.068	2.313	14.439
36	2.789	0.489	4.460	3.121	2.466	12.355
37	2.452	0.602	4.188	3.292	2.312	12.876
Critical *t*	2.712	0.342	4.182	3.694	2.144	13.375

tions. In addition to the above mention investigation of results of the *t*-statistic method which is applied to the equation developed, can be useful. The critical *t*-values are shown in Table 7. *t*-values higher than the critical *t*-values show that the equation has no statistical significance.

In Table 7, having higher *t*-values than the critical *t*-value, a lot of equations are statistically significant beca-

Table 8. Results of the compilations.

Location	Equation number
The whole country	17, 22, 29, 33, 36
Sana'a	21, 33
El Boun	16, 28
Hodeidah	19, 31
El Khaber	23, 35
Taiz	16, 28
El Macha	22, 34

use of having lower *t*-values than the critical *t*-value.

Equations of Group I and III has unlogical results, but equations of Group II and IV showed good and logical results in case of Sana'a, El Khaber and El Macha. In case of El Boun equations of Group I and III gave significant results, but equations of Group II and IV could not. In case of Hodeidah Eq. (15), (16), (19), (22), (27), (28), (31) and (34) are significant. Taiz has the least number of significant equations, i.e. only 6, and these are Eq. (15), (16), (19), (27), (28) and (31).

A summary of the developed equations which gave the better results, according to the whole country and cities can be clearly seen in Table 8. As can be understood from Tables 5, 6, 7 and 8, for the whole country, the equations which include two periods of the year, summer and winter, should be preferred because of having the best results and also for Sana'a, El khaber and El Macha. But for El Boun, Hodeidah and Taiz equations developed for the whole year are preferred because of the better results.

Having approximately the same performance, comparison of S/S_o and S/S_{nh} ratios is more difficult.

CONCLUSIONS

In this study, first of all it was seen that the clear sky solar radiation can be used to estimate the global radiation in Yemen.

It was seen that the equations which include the summer and winter periods gave the better results, than the others in all of the developed equation (Table 5). It is a predictable result that the performance of the equations are different for the whole country and for the cities.

Eq. (17), (19) – (22), (24), (29), (31) – (33) and (36) gave the best results among all of the developed equations. It can be said that all the analyses were harmonious.

Finally these results clearly indicate that reliance on the RMSE and MBE used separately can lead to a wrong decision in selecting the best model suited from the candidate models and that the use of the RMSE and MBE in isolation is not an adequate indicator of model performance. Therefore, the *t*-statistic should be used in conjunction with these two indicators to better evaluate a model's performance.

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Nomenclature

G_{on} = the extraterrestrial radiation, measured on the plane normal to the radiation on the *n*th of the year (W m^{-2})
G_{sc} = solar constant (1367 W m^{-2})
G_{cb} = the clear sky beam radiation (W m^{-2})
G_{cd} = the clear sky diffuse radiation (W m^{-2})
H = monthly mean daily global radiation on a horizontal surface (MJ m^{-2})
H_c = clear sky monthly mean daily global radiation on a horizontal surface (MJ m^{-2})
H_o = monthly mean daily extraterrestrial radiation (MJ m^{-2})
G_c = the clear sky global solar radiation (W m^{-2})
S = monthly average daily hours of bright sunshine
S_o = monthly average of maximum possible daily hours of bright sunshine (i.e. day length of average day of the month)
S_{nh} = monthly mean sunshine duration taking into account the natural horizon of site
a, b = empirical constants
a', b' = empirical constants
A = altitude (km)

Greek symbols

θ_z = zenith angle (degree)
τ_b = atmospheric transmittance for beam radiation
τ_d = atmospheric transmittance for diffuse radiation
ω = the sunset hour angle, the angular displacement of the sun east or west of the local meridian due to the rotation of the earth on its axis at 15° per hour (morning negative afternoon positive), in degrees
Φ = latitude, the angular location north or south of the equator, north positive
δ = declination angle