Estimation of Global Solar Radiation on Horizontal Surfaces Over Egypt

A. A. El-Sebaii[1*] and A. A. Trabea [2]

[1] Physics Department, Faculty of Science, Tanta University, Tanta, Egypt
[2] Physics Department, Faculty of Education, Suez Canal University, Al-Arish Branch, Egypt

The measured data of the monthly average global solar radiation on a horizontal surface $\overline{H}$ and the number of bright sunshine hours $\overline{n}$ for five locations in Egypt are analyzed. The selected locations represent the various weather conditions of Egypt. Matruh, Rafah and Al-Arish are in the north, Tanta in the middle and Aswan in the south. The regression constants for the first, second and third order Angström type correlations for each location have been calculated using the method of regression analysis. Comparisons between measured and calculated values of $\overline{H}$ are performed for the present locations. The values obtained for the RMSE, MBE and the MPE indicated that the second and third order Angström type correlations do not improve the accuracy of estimation of global radiation. Therefore, the measured data available for the selected locations are combined and a first order correlation has been proposed for all Egypt. Moreover, all Egypt correlation is extended to other Egyptian locations which are not included in the regression analysis. Comparisons between measured and calculated global radiation indicated that all Egypt correlation is applicable for any location of Egypt and may be extended outside Egypt for places which have the same values of the maximum clearness index (a + b).

1. Introduction:

In any solar energy conversion system, the knowledge of global solar radiation is extremely important for the optimal design and the prediction of the system performance. The best way of knowing the amount of global solar radiation at a site is to install pyranometers at many locations in the given region and look after their day-to day maintenance and recording, which is a very costly exercise. The alternative approach is to correlate the global solar

[*]Author for correspondence: Fax: 040-3380504; e-mail: aasebaii@yahoo.com

radiation with the meteorological parameters at the place where the data is collected. The resultant correlation may then be used for locations of similar meteorological and geographical characteristics at which solar data are not available.

The first correlation proposed for estimating the monthly average daily global solar radiation on a horizontal surface $\overline{H}$ (MJ/m^2 day) using the sunshine duration data is due to Angström [1]. Prescott [2] has put the Angström correlation in more convenient form as

$$\overline{H} / \overline{H}_o = a + b(\overline{n} / \overline{N}), \tag{1}$$

where $\overline{H}_o$ is the monthly average daily extraterrestrial radiation (MJ/m^2 day), $\overline{n}$ is the monthly average daily bright sunshine hours, $\overline{N}$ is the maximum possible monthly average daily sunshine hours or the day length and *a* and *b* are constants.

A number of correlations which include more meteorological parameters such as latitude, ambient temperature, the total precipitation, relative and specific humidity, the elevation, amount of cloud cover .etc have been developed by different workers [3-10]. Equation (1) has been found to be very convenient to a large number of locations and the most widely used correlation [3, 6, 9]. A new method has been proposed by Karsten [11] to evaluate the coefficients of Eq. (1) *a* and *b*. He assumed that *a* has the physical meaning of the monthly average daily diffuse radiation transmittance $\overline{H}_d / \overline{H}_0$ and *b* has the meaning of the monthly average daily beam radiation transmittance $\overline{H}_b / \overline{H}_0$. Singh et al [12], Fagbenle [13], Shaltout [14] and Ulgen and Hepbasli [15] have estimated a new set of constants for the second and third order Angström type correlations. It has been concluded that the second or the third order correlations give the best overall estimate of global solar radiation on a horizontal surface. Recently, Ulgen and Hepbasli [16] have correlated the global and diffuse radiation with respect to the ambient temperature in the fifth order polynomial form for Izmir in Turkey. They have outlined that their model predicts the global and diffuse solar radiation on horizontal surfaces reasonably well with correlation coefficients over 0.95.

The objective of the present study is to present and analyze the global solar radiation and sunshine duration data recorded at five cities (Matruh, Rafah, Al-Arish, Tanta and Aswan) in Egypt, and to develop new constants for the first, second and third order Angström type correlations which may be used for estimating $\overline{H}$ at any location of Egypt. Performance of the new constants is checked by comparing the estimated and measured values of global solar radiation. Statistical comparisons between measured and estimated global solar radiation indicated that the second and third order Angström type correlations do not improve the accuracy of estimation of global solar radiation. Therefore, first order or linear correlations between the monthly average daily clearness index $\overline{H}/\overline{H}_o$ and the relative possible sunshine duration $\overline{n}/\overline{N}$ for the selected locations and also for all Egypt have been proposed. All Egypt correlation is then extended to other four Egyptian locations not included in the regression analysis. It is concluded that the correlation proposed for all Egypt can be used successfully for estimation of $\overline{H}$ for any location of Egypt with a reasonable accuracy and may be extended outside Egypt for locations of similar meteorological characteristics.

2. Methodology:

The most widely used relationship to estimate monthly average daily global radiation on a horizontal surface $\overline{H}$ is that given by Angström [1], Eq. (1). The following second and third order Angström type correlations have been also proposed by different authors [12-14, 16]

$$\overline{H}/\overline{H}_o = a + b(\overline{n}/\overline{N}) + c(\overline{n}/\overline{N})^2, \qquad (2)$$

$$\overline{H}/\overline{H}_o = a + b(\overline{n}/\overline{N}) + c(\overline{n}/\overline{N})^2 + d(\overline{n}/\overline{N})^3, \qquad (3)$$

where *a*, *b*, *c* and *d* are the regression constants that depend on the location. The data of global radiation, which measured by the Epply Precision Pyranometers (with linearity $\pm$ 5% from 0 to 2800 W/m^2, accuracy better than 0.5% and resolution of 1 W/m^2) and the number of bright sunshine hours for five locations in Egypt are used in linear and multilinear regression analysis to find the regression constants of Eqs. (1)-(3). For all locations except for Tanta, the data measured on a period of 5 years (1990-1992) are used for the present analysis. For Tanta, the data measured during three years (1986-1988) are employed [17]. Table 1 gives a list of the five locations and their geographical locations. Proper computer programs are prepared for the analysis. The monthly mean daily extraterrestrial radiation $\overline{H}_o$ and the maximum possible monthly average daily sunshine duration $\overline{N}$ needed for the calculations are estimated using the standard procedure [18]. The developed correlations are then employed to calculate the global radiation for the five locations. The calculated values of global radiation are then compared with the measured data for these locations. The accuracy of the estimated global radiation data is tested by calculating the mean bias (MBE), root mean square (RMSE) and the mean percentage (MPE) errors. The MBE (MJ/m^2 day), RMSE (MJ/m^2 day) and MPE (%) are defined as follows:

$$MBE = [\sum (\overline{H}_{i,cal} - \overline{H}_{i,meas})]/n, \quad (4)$$

$$RMSE = \{[\sum (\overline{H}_{i,cal} - \overline{H}_{i,meas})^2 / n\}^{1/2}, \quad (5)$$

$$MPE = [\sum (\frac{\overline{H}_{i,meas} - \overline{H}_{i,cal}}{\overline{H}_{i,meas}} \times 100)]/n, \quad (6)$$

where $\overline{H}_{i,cal}$ and $\overline{H}_{i,meas}$ is the ith calculated and measured values and *n* is the total number of observations. In general, a low RMSE is desirable. The positive MBE shows overestimation while a negative MBE indicates underestimation.

Table (1): Geographical locations of the selected stations.

Location	Latitude (N)	Longitude (E)	Elevation (m)
Matruh	$31^\circ\ 21'$	$27^\circ\ 13'$	38.0
AL-Arish	$31^\circ\ 07'$	$33^\circ\ 45'$	32.0
Rafah	$31^\circ 13'$	$34^\circ\ 12'$	73.0
Tanta	$30^\circ\ 47'$	31°	8.0
Aswan	$23^\circ\ 58'$	$32^\circ\ 47'$	191.7

3. Results and discussions:

The locations selected in the present study are Matruh, Rafah and Al-Arish (north Egypt); Tanta (middle Egypt) and Aswan (south Egypt). The analysis of the measured and calculated $\overline{H}$ shows that for all locations in concern, the maximum values of global solar radiation are observed in June while the minimum values are appeared in December. The obtained values of the regression constants of Eqs. (1)-(3) along with the correlations regression coefficients (RC) and the values of the MBE, RMSE and MPE for the five locations are summarized in Table 2. From the results of Table 2 it is obvious that for all selected locations, the values of the regression coefficients (RC) of the proposed correlations are higher than 0.95 which indicate excellent fitting between the clearness index $\overline{H}/\overline{H}_o$ and the relative possible number of sunshine hours $\overline{n}/\overline{N}$. Furthermore, there is a remarkable agreement between the measured and calculated values of global radiation for the five locations. The RMSE and MPE values are also very low, indicating fairly good agreement. The negative values of the MPE indicate that the present correlations slightly overestimate $\overline{H}$. The highest value of the MPE equals 1.39% that obtained for the second order correlation proposed for Tanta. As also seen from the values of the RC, MBE, RMSE and the MPE the second and third order Angström type correlations do not significantly improve the accuracy of estimation of global solar radiation for the five locations. The latter results are also confirmed for each month for all locations under study. Comparisons between measured and calculated $\overline{H}$ estimated using Eqs. (1)-(3) along with the regression constants given in Table 2 indicated that the percentage error for a single month rarely exceeds $\pm 10\%$ in any of the locations. Again, the second and third order correlations do not increase the accuracy of estimation of global radiation. For example, the estimated annual average daily values of global solar radiation at Matruh are obtained as 20.018, 20.020 and 20.020 (MJ/m^2.day) using Eqs. (1), (2) and (3) respectively; while, the measured value equals 19.964 (MJ/m^2. day). The corresponding values for Aswan are found to be 22.123, 22.126 and 22.096 (MJ/m^2. day) compared to the measured value which equals 22.094 (MJ/m^2. day). From the above results it can be concluded that the following simple first order Angström correlations can be used for estimation of $\overline{H}$ on a horizontal surface at the five locations under study:

1. *Al-Arish*

$$\overline{H}/\overline{H}_o = 0.295 + 0.423(\overline{n}/\overline{N}), \quad (7)$$

2. *Rafah*

$$\overline{H}/\overline{H}_o = 0.367 + 0.342(\overline{n}/\overline{N}), \quad (8)$$

3. *Matruh*

$$\overline{H}/\overline{H}_o = 0.508 + 0.186(\overline{n}/\overline{N}), \quad (9)$$

4. *Tanta*

$$\overline{H}/\overline{H}_o = 0.247 + 0.489(\overline{n}/\overline{N}), \quad (10)$$

5. *Aswan*

$$\overline{H}/\overline{H}_o = 0.334 + 0.389(\overline{n}/\overline{N}), \quad (11)$$

It is seen from Eqs. (7 - 11) that neither *a* nor *b* vary with latitude or altitude in any systematic manner. However, the values of the sum of the regression constants $a+b$; which represent the maximum clearness index ($(\overline{n}/\overline{N}) = 1$) averaged over the period of recording the data, are found to be almost equal for the considered locations. The values of the sum $a+b$ are obtained as 0.718, 0.709, 0.694, 0.736 and 0.723 for Al-Arish, Rafah, Matruh, Tanta and Aswan, respectively.

Table (2): Regression constants of Eqs. (1) – (3) for the selected locations and the corresponding values of the RC, MBE, RMSE and the MPE.

Location	Degree of correlation	RC	Regression constants a	b	c	d	MBE	RMSE	MPE (%)
Rafah	First	0.965	0.367	0.342			0.004	0.014	-0.67
	Second	0.968	0.913	-1.204	1.074		0.003	0.011	-0.61
	Third	0.995	-0.418	4.529	-7.081	3.831	0.002	0.008	-0.52
AL-Arish	First	0.970	0.295	0.423			-0.007	0.023	-0.08
	Second	0.974	0.444	0.017	0.271		-0.007	0.024	-0.07
	Third	0.984	-0.213	2.736	-3.454	1.690	-0.007	0.024	-0.07
Matruh	First	0.973	0.508	0.186			0.005	0.016	-0.03
	Second	0.974	0.471	0.297	-0.081		0.005	0.016	-0.03
	Third	0.982	-0.123	3.087	-4.330	2.103	0.005	0.016	-0.02
Tanta	First	0.960	0.247	0.489			0.0183	0.063	-0.52
	Second	0.987	-0.992	3.711	-2.065		0.033	0.115	-1.39
	Third	0.991	-1.004	3.782	-2.193	0.062	0.019	0.065	-0.55
Aswan	First	0.950	0.334	0.389			0.002	0.008	-0.13
	Second	0.959	3.383	-6.780	4.201		0.003	0.009	-0.18
	Third	0.977	23.82	88.76	-107.4	43.41	0.0001	0.0004	-0.10

Since, the second and third order correlations between $\overline{H}/\overline{H}_o$ and $\overline{n}/\overline{N}$ do not improved the accuracy of estimation of $\overline{H}$, the measured data available for the five selected locations are combined and analyzed in order to develop a first order correlation for all Egypt. The following linear correlation has been obtained for all Egypt:

$$\overline{H}/\overline{H}_o = 0.3647 + 0.3505(\overline{n}/\overline{N})\,; \qquad (12)$$

with RC = 0.984 and a maximum clearness index equal 0.715. Similar results are obtained for some locations at Yemen Arab Republic (YAR) [19]; where, the values of $a+b$ are found in the range 0.695-0.716.

Equation (12) is then employed for estimating $\overline{H}$ for the five locations. Some examples of comparisons between measured and calculated $\overline{H}$ (estimated using all Egypt correlation) are shown in Figs. 1, 2 and 3 for Rafah, Tanta and Aswan, respectively. A fairly good agreement between measured and calculated global radiation for all locations is clear. The percentage error for estimating $\overline{H}$ for Tanta and Matruh for a single month never exceeds $\pm 12\%$;

however, for the other locations (Al-Arish, Rafah and Aswan) it is less than $\pm 9\%$. Furthermore, Eq. (12) is also employed for estimating the monthly average daily global radiation for other Egyptian locations which are not included in the present regression analysis. These locations include Cairo (Lat. $30^\circ\ 05'$), Bahtim (Lat. $30^\circ\ 09'$), Tahrir (Lat. $30^\circ\ 39'$) and Asyuot (Lat. $27^\circ\ 12'$). The measured data (monthly average daily global radiation and bright sunshine hours) for these locations are taken from the data given by Kamel et al. [20]. Figures (4-7) present comparisons between measured and calculated, using Eq. (9), $\overline{H}$ for Cairo (Fig. 4), Bahtim (Fig. 5), Tahrir (Fig. 6) and Asyuot (Fig. 7). From the results of these figures it is obvious that the agreement between measured and calculated data for all locations that are not included in the regression analysis is excellent. It is found that Eq. (9) can be used for estimating $\overline{H}$ at Cairo, Bahtim, Tahrir and Asyuot with absolute values of the MPE of about 2.4, 3.5, 5.9 and 3.6%, respectively. The values of the MBE are found to be 0.032, 0.042, 0.085 and 0.054 for Cairo, Bahtim, Tahrir and Asyuot, respectively. The low values of the RMSE, MBE and the MPE clearly prove that the proposed correlation for all Egypt, Eq. (9), can be used for estimation of global solar radiation on a horizontal surface at any location of Egypt.

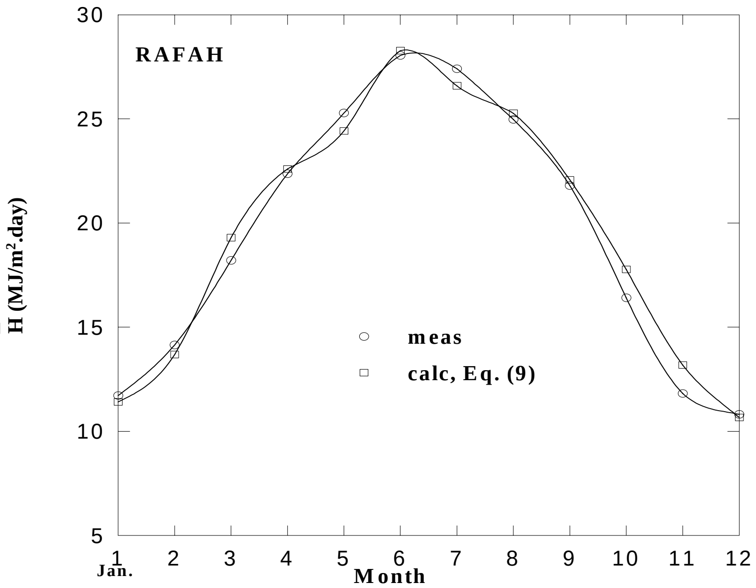

Fig. (1): Comparisons between measured and calculated monthly average global solar radiation on a horizontal surface $\overline{H}$ at Rafah. Calculations performed using all Egypt correlation, Eq. (9).

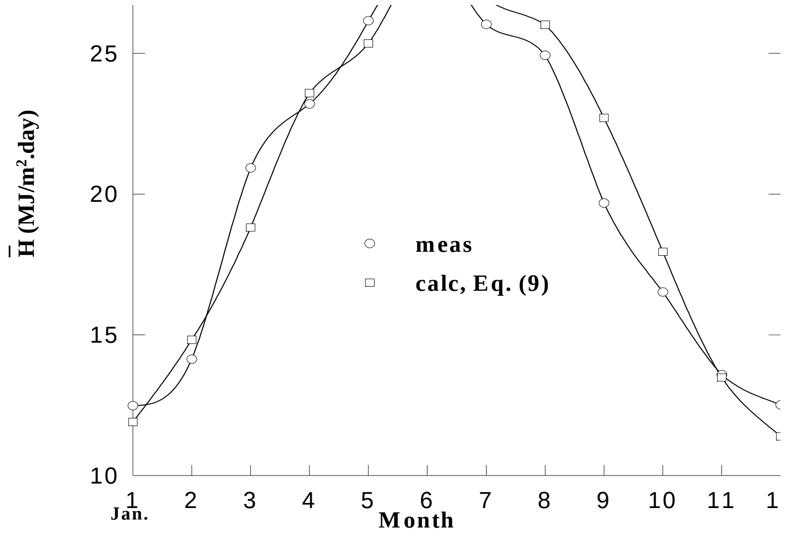

Fig. (2): As the same for Fig. 1 but for Tanta.

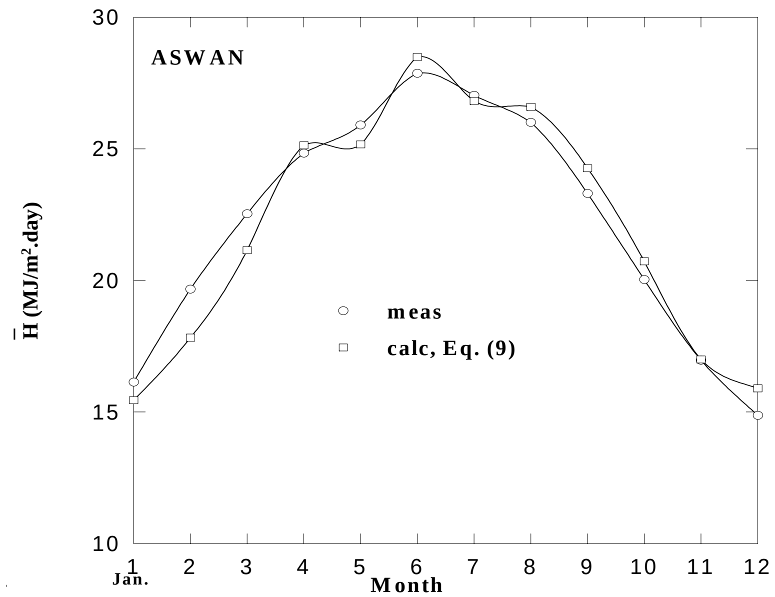

Fig. (3): As the same for Fig. 1 but for Aswan.

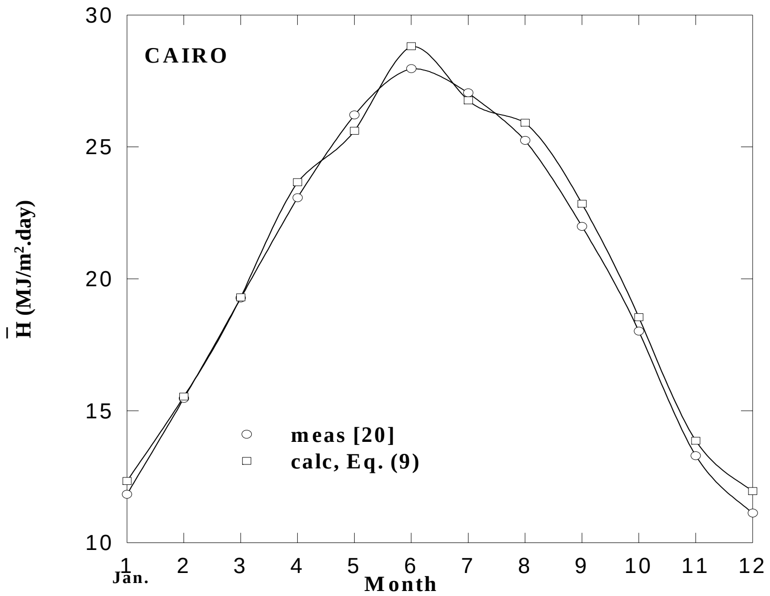

Fig. (4): Comparisons between measured and calculated $\overline{H}$ for Cairo. Calculations performed using all Egypt correlation, Eq. (9). Measured data are not included in the regression analysis.

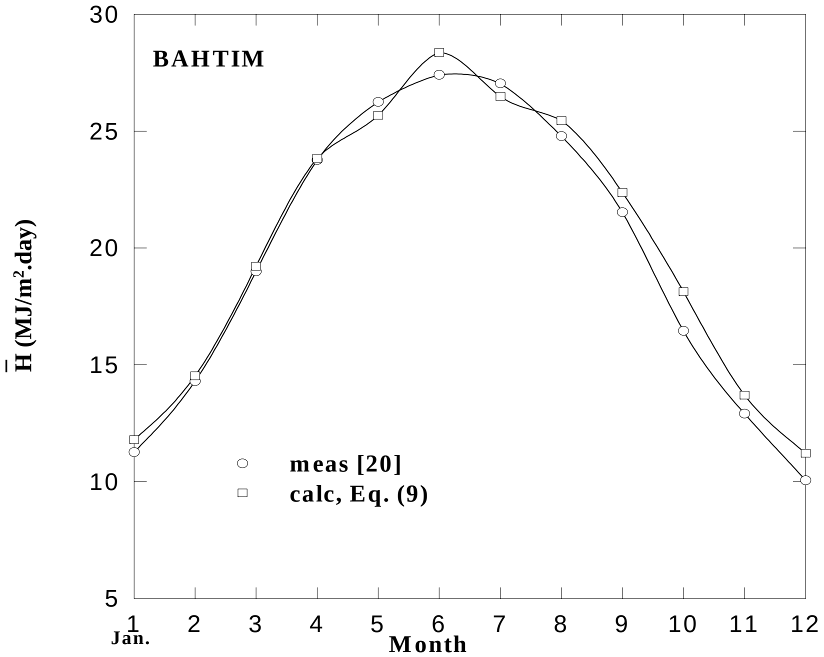

Fig. (5): As the same for Fig. 4 but for Bahtim.

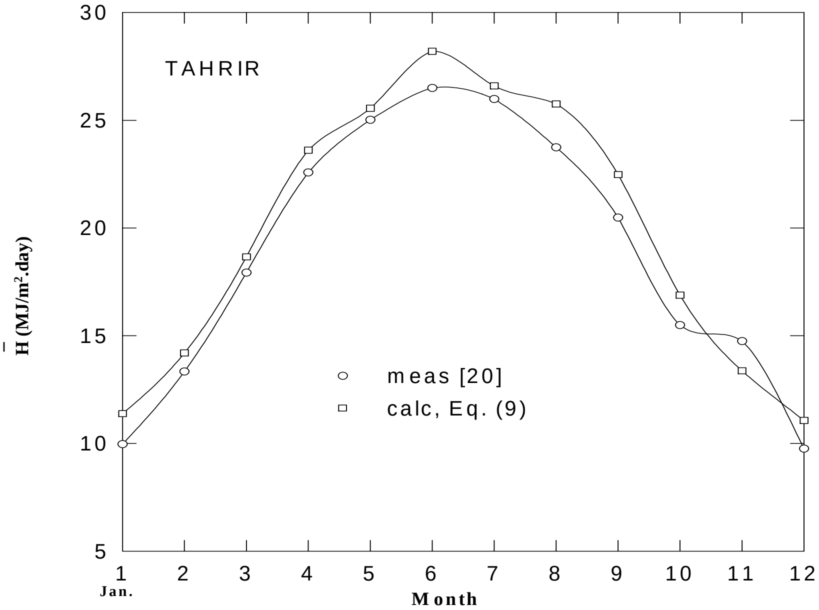

Fig. (6): As the same for Fig. 4 but for Tahrir.

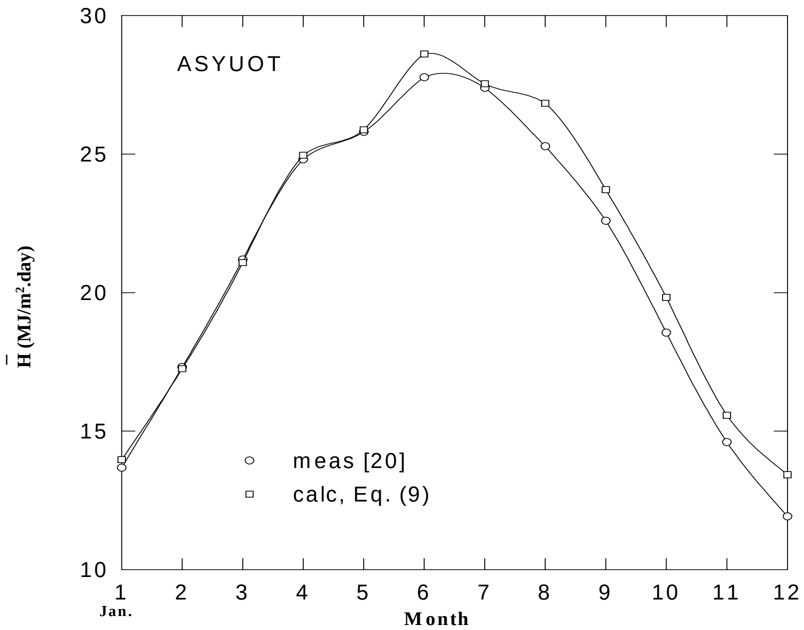

Fig. (7): As the same for Fig. 4 but for Asyuot.

Since, the maximum clearness index ($a+b$) obtained from all Egypt correlation is found to be almost equal to that obtained for YAR (see Table 5 in Ref. 19), Eq. (12) is also used to estimate $\overline{H}$ for some cities in YAR. The calculated data of $\overline{H}$ are compared with the measured ones given in Ref. 19. The obtained results are summarized in Table (3) for five cities in YAR which include Sana'a, Taiz, El Macha, Al Khaber and El Boun. It is seen from the results of Table 3 that the agreement in general is fairly good. The relative percentage difference between measured and calculated global radiation (PE) for all cities for a single month (except on August or September for Sana'a, Al khaber and Al Boun) rarely exceeds 5% and in most cases it is much less. It is also obvious from the low values obtained for the RMSE and the MBE that all Egypt correlation estimates the monthly and annual averages daily of global radiation for the present YAR cities with very good accuracy; consequently, the long-term performance of solar energy devices can be estimated.

Table (3). Comparisons between measured [19] and calculated (Eq. (9)) monthly average daily global radiation (MJ/m^2 day) at some cities in YAR.

Month	Town / Month	**Sana'a 15.51^o N**	**Taiz 13.58^o N**	**El Macha 13.25^o N**	**Al Khaber 14.38^o N**	**El Boun 15.73^o N**
J	$\overline{H}_{meas}$	19.35	18.30	18.00	17.50	17.10
	$\overline{H}_{calc}$	18.06	17.04	17.47	17.55	16.88
	PE (%)	6.66	6.88	2.95	-0.29	1.30
F	$\overline{H}_{meas}$	21.33	20.60	20.00	21.60	22.40
	$\overline{H}_{calc}$	20.38	19.69	19.75	20.85	21.03
	PE (%)	4.46	4.43	1.25	3.47	6.10
M	$\overline{H}_{meas}$	20.63	21.30	23.00	21.80	21.70
	$\overline{H}_{calc}$	21.98	22.59	22.00	22.28	22.63
	PE (%)	-6.55	-6.05	4.37	-2.21	-4.28
A	$\overline{H}_{meas}$	23.53	20.90	25.00	24.40	23.70
	$\overline{H}_{calc}$	24.07	24.51	23.73	25.61	24.59
	PE (%)	-2.28	-17.27	5.06	-4.96	-3.76
M	$\overline{H}_{meas}$	22.83	21.20	23.50	23.90	22.50
	$\overline{H}_{calc}$	23.46	23.08	23.67	24.19	23.79
	PE (%)	-2.76	-8.86	-0.73	-1.24	-5.74

J	$\overline{H}_{meas}$	24.27	21.20	22.40	22.50	23.10
	$\overline{H}_{calc}$	24.31	22.67	22.40	24.39	24.59
	PE (%)	-0.17	-6.91	-0.01	-8.43	-6.44
J	$\overline{H}_{meas}$	20.23	20.00	21.70	19.60	21.80
	$\overline{H}_{calc}$	21.36	20.14	21.02	21.26	22.02
	PE (%)	-5.58	-0.69	3.13	-8.45	-1.01
A	$\overline{H}_{meas}$	19.50	21.30	21.20	18.80	22.30
	$\overline{H}_{calc}$	22.28	22.00	21.66	21.38	22.83
	PE (%)	-14.26	-3.29	-2.18	-13.72	-2.37
S	$\overline{H}_{meas}$	23.13	21.10	21.00	21.30	21.20
	$\overline{H}_{calc}$	23.47	21.99	22.01	23.35	23.88
	PE (%)	-1.45	-4.20	-4.80	-9.61	-12.65
O	$\overline{H}_{meas}$	22.23	21.50	22.40	22.20	24.20
	$\overline{H}_{calc}$	22.47	22.12	22.39	23.10	22.63
	PE (%)	-1.06	-2.88	0.06	-4.05	6.51
N	$\overline{H}_{meas}$	19.57	19.30	20.70	20.70	22.20
	$\overline{H}_{calc}$	19.28	19.17	19.98	20.07	19.46
	PE (%)	1.46	0.67	3.46	3.04	12.37
D	$\overline{H}_{meas}$	19.17	18.00	18.80	19.80	19.70
	$\overline{H}_{calc}$	18.15	18.04	18.47	19.23	18.33
	PE (%)	5.34	-0.21	1.73	2.90	6.96
Annual Average						
	$\overline{H}_{meas}$	21.314	20.392	21.475	21.175	21.825
	$\overline{H}_{calc}$	21.605	21.085	21.213	21.939	21.887
	PE (%)	-1.35	-3.20	1.19	-3.63	-0.25
RMSE		0.08	0.02	0.08	0.02	0.02
MBE		0.02	0.05	-0.02	0.06	0.01

4. Conclusions:

On the basis of the obtained results for five locations in Egypt, the following conclusions may be drawn: (i) The second and third order Angström type correlations do not significantly improve the accuracy of estimation of the monthly average daily global radiation incident on a horizontal surface $\overline{H}$. Therefore, a first order correlation is proposed for each location, Eqs. (4) - (8). (ii) The proposed first order correlations are able to predict the global radiation with percentage error for a single month never exceeds $\pm 10\%$ in any of the locations. (iii) The proposed correlation for all Egypt, Eq. (9), can be used for estimating $\overline{H}$ for any location of Egypt with absolute values of the MPE less than 6%. All Egypt correlation may be extended outside Egypt for places which have the same values of the maximum clearness index.

References:

1. A. Angström, *Q. J. Roy. Met. Soc*. **50**, 121 (1924).
2. J.A. Prescott, *Trans. Roy. Soc. Austr*. **64**, 114 (1940).
3. K.K. Gopinathan, *Solar Energy* **41** (6), 499 (1988).
4. N. Halouani, C.T. Nguyen, D. Vo-Ngoc, *Solar Energy,* **50** (3), 247 (1993).
5. H.P. Garg and S.N. Garg, *Energy Convers. Mgmt*., **23** (2), 113 (1983).
6. Lin Venxian. Solar Energy, **41** (1), 1 (1988).
7. B.S. Attili and Y.A.G. Abdalla, *Energy Convers. Mgmt*., **34** (1), 1 (1993).
8. I. Supit and R.R. Vankappel, *Solar Energy,* **63** (3), 147 (1998).
9. S. Ahmed and Taher Abuain. *Energy Convers. Mgmt*., **33** (2), 117 (1992).
10. A.A. Trabea, M.A. Mosalam Shaltout, *Renewable Energy,* **21**, 297 (2000).
11. Karsten Hinrichsen, *Solar Energy,* **52** (6), 491 (1994).
12. O.P. Singh and S.K. Srivastawa, Gaur, *Energy Convers. Mgmt*., **37** (4), 501 (1996).
13. R. Layi Fagbenle, *Int. J. Energy Research,* **16**, 583 (1992).
14. M.A. Mosalam Shaltout, *ASRE*, **1** (4), 35 (1986).
15. K. Ulgen and A. Hepbasli, *Int. J. Energy Research,* **26**, 413 (2002).
16. K. Ulgen and A. Hepbasli, *Int. J Energy Research,* **26**, 807 (2002).
17. A.A. El-Sebaii, *M. Sc. Thesis,* Tanta University, Egypt (1989).
18. J.A. Duffie and W.A. Beckman, "*Solar engineering of thermal processes*", 2nd edition. New York: Jon Wiley and Sons Inc., (1991).
19. A. Khogali, M.R.I. Ramadan, Z.E.H. Ali and Y.A. Fattah, *Solar Energy*, **31**(1), 55 (1983).
20. M.A. Kamel, S.A. Shalaby and S.S. Mostafa, *Solar Energy*, **50** (6), 463 (1993).