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On the estimation of global and diffuse solar radiation over Egypt

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सार – इस शोध पत्र में अनुमानित भूमंडलीय और विसरित सौर विकिरण के आकलन की कुछ पद्धतियों की वैधता की जाँच करने के लिए नौ मौसम विज्ञान केंद्रों में भूमंडल के मापों, *H* विसरित , *D* क्षैतिज सतह पर सौर विकिरण और धूप की अवधि, *n* का उपयोग किया गया है। पूर्वानुमान देने के लिए प्राप्त किए गए परिणामों में सुधार लाने के लिए मिस्र के जांच किए गए क्षेत्र को नौ चुने हुए केंद्रों (शीत और उष्ण ऋतुओं) के रूप में पाँच क्षेत्रों में विभाजित किया गया है। प्रत्येक क्षेत्र के लिए बारबर्रा के आनुभविक संबंधों को उपयुक्त क्षेत्रीय प्राचल, *K* में निर्धारित किया गया है। मापों और अनुमानित मानों के परस्पर संबंध महत्वपूर्ण है। अनुमानित मानों की अधिकतम संभावित त्रुटि 9.6% से अधिक नहीं है। यह देखा गया है कि संशोधित सत्र से मिस्र के किसी भी इलाके में भूमंडलीय सौर से विकिरण के लिए सुस्पष्ट आकलन प्राप्त होते हैं प्रत्येक क्षेत्र के लिए विसरित खंडों, *D*/*H* और धूप की सापेक्षिक अवधि, अवधि *n/N* के परस्पर संबंध भी निर्धारित किए गए है। इनसे प्राप्त किए गए संबंधों को लागू करते समय मापित और आकलित मानों के मध्य बेहतर मेल पाया गया है। अतः मिस्र के किसी भी इलाके में उपयोग के लिए इन संबंधों की सिफारिश की गई। मिस्र के विभिन्न स्थानों में भूमंडलीय और विसरित सौर विकिरण के लिए तुलनात्मक अध्ययन किए गए।

ABSTRACT. Measurements of global, *H*, diffuse, *D*, solar radiation on a horizontal surface and sunshine duration, *n*, at nine meteorological stations have been used to examine the validity of some methods of the estimate global and diffuse solar radiation. In order to improve the obtained results, for prediction purposes, the investigated area of Egypt has been divided into five regions represented by the nine selected stations (in cold and hot seasons). An appropriate regional parameter, *K*, of an empirical relation of Barbaro *et al*. has been determined for each region. The agreement between measurement and estimated values is remarkable. The maximum possible error of estimated values does not exceed 9.6%. It is seen that the modified formula gives precise estimations for global solar radiation at any Egyptian locality. Relation between the diffuse fraction, *D/H,* and the relative duration of sunshine, *n/N,* are also determined for each region. Good agreement between the measured and estimated values applying the obtained relations has been found. Therefore, the relations are recommended for use at any location in Egypt. A comparative study for the global and diffuse solar radiation over different sites in Egypt has been made.

Key words – Global radiation, Diffuse radiation, Egypt, Sunshine duration.

1. Introduction

The design of any solar energy conversion system requires the knowledge of solar radiation data, obtained over a long period of time. For many countries, these data are not available. Therefore, for locations where measured data are not available, empirical relations developed by various investigators are used in estimating global and diffuse solar radiation values using easily obtainable meteorological parameters such as sunshine duration, relative humidity, minimum and maximum temperature, cloud cover and geographical location.

Swartman and Ogunlade, 1967 used the relative humidity in addition to the sunshine hours in establishing their formula. Reddy, 1971 suggested the use of the number of rainy days, sunshine hours and a factor which depends on the latitude and geographical location of the place relative to the sea, in calculating the daily total radiation. Sayigh, 1977 derived his equation by using sunshine duration, relative humidity and temperature. Sabbagh *et al*., 1977related daily total solar radiation to the sunshine duration, relative humidity, maximum temperature, latitude, altitude and the location of the place relative to the sea. Hoyt, 1978 developed a more complicated theoretical model to give the global irradiation falling on the earth's surface. Climatological values of total precipitable water, turbidity and surface albedo was required as the model inputs.

In Egypt, El-Shahawy, 1984 proposed a semi-empirical formula for estimating the global solar radiation.

This formula essentially requires: the latitude, sun's declination, clouds amount and type and back scattering. He found good agreement between estimated and measured values of global radiation on monthly and daily basis. El-Shazly, *et al*., 1998, studied the solar radiation characteristics at Qena/ Upper Egypt. They used the measurements of the hourly global and diffuse solar radiation on a horizontal surface of Qena in the period from June 1992 to May 1993. They discussed the seasonal and climatic effects on the fluctuation of the different components of solar radiation. They found that these effects were particularly large during spring and winter months owing to the high fluctuation of the atmospheric conditions with respect to cloud amounts, water content, and concentration of aerosol dust particles. They also found that the relative reduction of global solar radiation by cloud over the whole period is around 4.5% due to the low degree of cloudiness in the study region.

Trabea and Shaltout, 2000 related the measurements of global solar radiation with five meteorological parameters namely: maximum air temperature, relative humidity, atmospheric pressure, vapor pressure and hours of bright sunshine at five selected locations over Egypt. They found that the values of correlation coefficients between the global radiation and the mentioned five meteorological parameters vary from 89% to 99% and the errors of estimation are between 0.01 and 0.04. Darwish and Taha, 2000 used the induced empirical formulae to estimate the diffuse radiation as a function of global solar radiation over the Eastern Arab Region. They found that the used formulae are available for regular observation for a long time at sufficient number of stations located in different climatic regions.

Although Egypt is a vast country, the number of its meteorological stations that measure the solar radiation components are only a few. Therefore, the main objective of this paper is to establish simple model to estimate the monthly mean daily global and diffuse solar radiation and hence direct solar radiation. An empirical relation of Barbaro *et al*., 1978 is very suitable to estimate the components of solar radiation at any time and locality in Egypt where there are no measured data of solar radiation components or there are instrumental and other difficulties encountered in measuring components of solar radiation. Computations have been made to illustrate that the proposed relation gives precise estimations of solar radiation components than other methods.

2. Methods of prediction

Sivkov, 1964 proposed original empirical relation to estimate the monthly mean global solar radiation at the latitudes from 35° to 65° N in the form :

$$H = 4.9\,(n)^{1.31} + 10550\,(\sin h)^{2.1} \tag{1}$$

where, H and n are the monthly global solar radiation (in cal cm^{-2}) and the monthly sunshine hours, respectively. h, is the noon altitude of the sun on the 15 of the month.

Barbaro *et al*., 1978 modified this formula to fit 31 Italian stations that they divided into three zones according to their climatological characteristics. The modified formula is ;

$$H = K(n)^{1.24}(h)^{-0.19} + 10550(\sin h)^{2.1} + 300(\sin h)^{3} \tag{2}$$

where, K = 8, 9.5, 11 for zone 1, zone 2 and zone 3 respectively. The computation of H is based on the knowledge of the appropriate zone parameter and long-term averages of sunshine hours and altitude of the sun.

Relation (2) which was proposed for high latitudes (35° - 65° N) was tested by Khogali, 1983 for low latitudes (4° - 19° N) and has been found applicable with a good degree of accuracy provided that the parameter K is appropriately adjusted.

The diffuse solar radiation could be estimated by the widely used empirical formula, which was developed by Page, 1961

$$D/H = 1 - 1.13K_T \tag{3}$$

Where D is the monthly average of the daily diffuse solar radiation, H is the monthly average of the daily global solar radiation and the ratio $K_T = H/H_0$ is the clearness index. The extraterrestrial solar radiation H_0 is obtained from Duffie and Beckman, 1974;

$$H_0 = \frac{24}{\pi} I_s \left(1 + 0.033 \cos \frac{360n'}{365}\right) \left(\cos\varphi \cos\delta \sin w + \frac{2\pi}{360} w \sin\varphi \sin\delta\right) \tag{4}$$

Where the solar constant I_s = 1369 ± 7 Wm^{-2}, n' is the day number (starting 1 January), w is the sunrise hour angle, φ is the latitude and δ is the sun declination.

Another commonly used relation is due to Liu and Jordan, 1960 and developed by Klein, 1977 to take the form :

$$D/H = 1.93 - 4.027K_T + 5.531(K_T)^2 - 3.108(K_T)^3 \tag{5}$$

The direct beam component is estimated from the relation;

$$I \sin h = H - D \tag{6}$$

TABLE 1

Coordinates of the Egyptian radiation measurements network and the radiation components measured together with the date of commencement of recording

Station	Latitude °N	Longitude °E	Elevat (m)	Measurements *H*	*D*	*I*	*S*	Date of commencement of records
Sidi-Barrani	31° 38′	25° 24′	27	X	X	-	X	1984
Matruh	31° 20′	27° 13′	38	X	X	-	X	1961 (1981)
El-Arich	31° 05′	33° 49′	32	X	X	-	X	1980
Tahrir	30° 39′	30° 42′	16	X	X	-	X	1960 (1981)
Bahtim	30° 08′	31° 15′	17	X	-	-	X	1969
Cairo	30° 05′	31° 17′	36	X	X	X	X	1969 (1974)
Asyut	27° 03′	31° 01′	52	X	-	-	X	1979
El-Kharga	25° 27′	30° 32′	78	X	X	-	X	1964 (1981)
Aswan	23° 58′	32° 47′	192	X	X	-	X	1972 (1981)

*The year in brackets indicates the data of commencement of diffuse and/or direct solar radiation records. *H* is the global solar radiation; *D* is the diffuse solar radiation, *I* is the direct solar radiation, and *S* is the sunshine duration.

Where the product, $I \sin h$, is the average horizontal beam component.

Although, there are many good formulae to estimate global solar radiation in Egypt, as mentioned above, the empirical relation (2) of Barbaro *et al*. 1978 has been chosen to estimate global solar radiation in Egypt for the following reasons :

(*i*) This formula has been applied for different latitudes (such as Italy, Yemen and Sudan) to estimate global solar radiation. It has been found that it gives better estimates of solar radiation compared to other methods.

(*ii*) This formula is independent of meteorological parameters such as the relative humidity, minimum and maximum temperature, cloud cover and other parameters. It requires only hours of sunshine and minimum optical depth of the persisting air mass as input parameters. Therefore, this formula is very suitable to be applicable at any locality especially in the absence meteorological stations and lack of measured data of solar radiation components.

3. Results and discussion

In this study, all stations in Egypt that measure solar radiation have been used. Table 1 gives a list of the nine selected stations and their coordinates in addition to the type of measured radiation at each station and it's date of commencement of records. In order to predict global and diffuse radiation with greater accuracy, the year has been divided into two seasons, cold season (October to February) and hot season (March to September). The investigated area has been divided into five regions according to the distribution of network of radiation

TABLE 2

Regions of Egypt and their represented stations with the values of the parameter, *K*

Region	Represented stations	Regional parameter, *K* Cold season	Hot season	All year
Region 1 Northern Egypt & Mediterranean coast	Sidi-Barrani Matruh El-Arich	12.4	14.6	13.7
Region 2 Lower Egypt & Delta	Tahrir Bahtim Cairo	12.3	15.1	13.9
Region 3 Middle Egypt	Asyut	14.3	16.8	15.8
Region 4 Western desert	El-Kharga	11.5	14.5	13.3
Region 5 Upper Egypt	Aswan	13.5	16.5	15.3
All Egypt	—	12.8	15.5	14.4

TABLE 3

The regional values of the parameter *K*, sunshine hours *n*, the noon altitude of the sun *h*, in addition to one year (1995) measured H_m and estimated H_c values of monthly mean global radiation (MJ/m^2.day) and their percentage error, *e*, at the different stations

Region & station		J	F	M	A	M	J	J	A	S	O	N	D
Region 1													
	K	12.4	12.4	14.6	14.6	14.6	14.6	14.6	14.6	14.6	12.4	12.4	12.4
	n	7.0	7.1	8.4	9.0	9.6	11.7	12.4	11.7	10.0	9.4	7.4	6.5
Sidi-Barrani	*h*	36.6	44.8	55.3	67.4	76.5	80.2	78.1	71.4	61.2	49.9	39.9	34.9
	H_c	11.8	14.4	19.2	22.7	24.4	28.0	28.4	26.7	23.4	17.7	13.2	10.9
	H_m	10.8	13.6	19.6	22.9	25.0	28.1	28.9	27.0	23.6	18.6	12.8	10.4
	e	-9.3	-5.9	2.0	0.9	2.4	0.4	1.7	1.1	0.8	4.8	-3.1	-4.8
	K	12.4	12.4	14.6	14.6	14.6	14.6	14.6	14.6	14.6	12.4	12.4	12.4
El-Arich	*n*	6.7	6.9	8.5	9.5	10.2	12.6	12.0	10.9	9.4	8.5	7.4	6.1
	h	37.4	45.7	56.7	66.6	77.5	81.5	79.4	72.5	61.9	50.5	40.5	35.6
	H_c	11.6	14.4	19.6	23.3	25.3	29.3	28.0	25.7	22.2	16.8	13.3	10.5
	H_m	10.8	14.0	19.8	23.5	25.6	29.7	28.4	26.0	22.6	16.8	12.8	10.0
	e	-7.4	-2.9	1.0	0.9	1.2	1.4	1.4	1.2	1.8	0.0	-3.9	-5.0
	K	12.4	12.4	14.6	14.6	14.6	14.6	14.6	14.6	14.6	12.4	12.4	12.4
Matruh	*n*	6.7	7.6	8.1	9.0	11.0	12.7	12.9	11.7	10.2	9.4	7.5	6.0
	h	36.1	44.0	54.4	66.4	74.9	77.9	75.7	69.9	60.5	49.7	39.9	34.7
	H_c	11.4	14.8	18.6	22.6	26.2	29.2	28.9	26.5	23.1	17.7	13.3	10.2
	H_m	10.4	14.0	19.5	23.1	26.9	29.7	29.7	26.8	23.3	17.8	13.0	9.8
	e	-9.6	-5.7	4.6	2.2	2.6	1.7	2.7	1.1	0.9	0.6	-2.3	-4.1
Region 2													
	K	12.3	12.3	15.1	15.1	15.1	15.1	15.1	15.1	15.1	12.3	12.3	12.3
Tahrir	*n*	7.2	7.1	8.3	9.6	10.0	12.2	12.0	11.1	10.2	8.7	7.1	6.2
	h	37.4	45.5	56.0	68.1	77.1	80.5	78.3	72.0	62.0	50.8	40.9	35.8
	H_c	12.2	14.5	19.5	24.0	25.4	29.1	28.3	26.4	23.8	17.0	13.0	10.6
	H_m	11.4	14.1	20.2	25.0	25.9	29.9	28.6	26.7	24.7	17.8	13.2	10.2
	e	-7.0	-2.8	3.5	4.0	1.9	2.7	1.0	1.1	3.6	4.5	1.5	-3.9
Bahtim	*K*	12.3	12.3	15.1	15.1	15.1	15.1	15.1	15.1	15.1	12.3	12.3	12.3
	n	7.1	7.4	8.3	9.8	10.2	11.9	11.9	11.1	10.1	8.7	7.9	6.0
	h	38.0	46.1	56.7	68.8	77.7	81.1	79.0	72.6	62.6	51.4	41.4	36.4
	H_c	12.2	15.0	19.7	24.4	25.7	28.8	28.2	26.5	23.7	17.2	14.1	10.5
	H_m	11.2	13.9	19.9	24.6	26.0	29.4	28.4	26.9	24.7	17.0	13.7	10.1
Cairo	*e*	-8.9	-7.9	1.0	0.8	1.2	2.0	0.7	1.5	4.0	-1.2	-2.9	-4.0
	K	12.3	12.3	15.1	15.1	15.1	15.1	15.1	15.1	15.1	12.3	12.3	12.3
	n	6.1	6.7	7.4	8.2	9.0	11.0	11.8	10.1	9.0	8.1	6.7	5.5
	h	38.1	46.2	66.7	68.8	77.8	81.2	79.0	72.7	62.6	51.4	41.5	36.4
	H_c	11.0	14.3	20.4	22.2	24.1	27.5	28.1	25.1	22.2	16.5	12.7	10.0
	H_m	10.2	13.3	19.3	22.9	24.0	27.9	27.3	25.0	21.8	16.2	12.4	9.7
	e	-7.8	-7.5	-5.7	3.1	-0.4	1.4	-2.9	-0.4	-1.8	-1.9	-2.4	-3.1
Region 3													
	K	14.3	14.3	16.8	16.8	16.8	16.8	16.8	16.8	16.8	14.3	14.3	14.3
	n	9.4	9.6	9.6	10.8	10.9	12.2	11.8	11.8	10.8	9.9	9.6	8.3
	h	38.1	46.2	56.7	68.8	77.8	81.2	79.0	72.7	62.6	51.4	41.5	36.4
El-Kharga	H_c	16.6	19.2	22.8	27.2	28.1	30.8	29.6	29.1	26.2	20.2	17.7	14.7
	H_m	15.8	18.4	23.0	27.9	28.5	30.9	30.2	29.2	27.1	20.4	16.9	13.8
	e	-5.1	-4.3	0.9	2.5	1.4	0.3	2.0	0.3	3.3	1.0	-4.7	-6.5
Region 4													
	K	11.5	11.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	11.5	11.5	11.5
	n	8.9	9.5	9.8	10.8	11.5	12.7	12.7	12.1	10.9	9.9	8.9	7.7
Asyut	*h*	41.0	49.1	59.6	71.6	80.3	83.0	80.9	75.2	65.5	54.4	44.5	39.4
	H_c	14.5	17.7	22.0	25.8	27.2	29.4	28.9	27.6	24.9	18.7	15.4	12.7
	H_m	14.4	18.0	21.9	26.4	27.4	30.1	28.8	26.8	24.1	19.3	15.3	12.6
	e	-0.7	1.7	-0.5	2.3	0.7	2.3	-0.3	-3.0	-3.3	3.1	-0.7	-0.8
Region 5													
	K	13.5	13.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	13.5	13.5	13.5
	n	10.1	10.3	10.5	10.8	11.0	12.2	12.4	11.6	10.4	9.7	9.2	9.0
	h	44.3	52.5	63.0	75.0	83.8	85.6	83.8	78.7	68.9	57.6	47.6	42.6
Aswan	*Hc*	18.3	21.1	25.2	27.8	28.4	30.6	30.5	29.0	26.4	20.7	18.0	16.4
	Hm	18.2	21.4	25.7	28.3	28.6	30.8	30.6	29.6	27.5	21.4	18.1	15.7
	e	-0.5	1.4	1.9	1.8	0.7	0.7	0.3	2.0	4.0	3.3	0.6	-4.5

stations. The divided regions and its represented stations are given in Table 2. Both region 1 and region 2 are represented by three stations while the other regions are represented by one station only.

3.1. *Computation of diffuse solar radiation*

The monthly mean daily values of measured global radiation, H_m, and sunshine hours, n, of the five years (1985 to 1989) in addition to h values for nine stations have been obtained from the Egyptian Meteorological Authority. The data of each region, represented by the concerned stations, have been studied and analyzed using the advanced computer programs and applying an empirical relation of Barbaro *et al*., 1978 to obtain the regional values of the parameter K. The results are given in Table 2.

Verification of the obtained regional values of the parameter, K, was carried out by estimating global radiation using measured data of n for the year 1995 at each of the selected station. The calculated data of global radiation, H_c, are presented in Table 3 where a comparison with measurements, H_m, of the same year, 1995, is also given. The relative percentage errors defined as : $e = \frac{H_m - H_c}{H_m} \times 100,$, are also given in the same table.

The agreement between experimental and estimated values is remarkable especially for non-cloudy months (May to August) at all stations whereas the possible error of estimated values, e, does not exceed 3% (Table 3). Also, good agreement between measured and estimated values has been found at both middle and southern regions whereas the maximum error of estimated values is found 3.3% and 4.5% for two regions respectively. The maximum error is found 9.6%, 8.9 % and 6.5 % for the northern, Lower Egypt and Delta and western desert regions respectively. For different cloudy conditions the maximum error of the estimated values is typically 9.6%. It is concluded that the error of estimated value relatively increases with the increase of cloud cover and *vise versa*. This is due to the factor of cloud effects is not taken in the consideration.

It may be noted that the method underestimates the global radiation all the year round except during the months from November to February. The overestimation takes its maximum value during January month at northern region and decreases gradually towards southern region. This is due to the corresponding effects of clouds and moisture, which are not considered in the estimation procedure.

At urban area of Cairo, the method overestimates the global radiation all the year round except during two months of April and June. This can readily be explained on the basis that pollutants and aerosols are high in Cairo's atmosphere during most months of the year causing a reduction of global radiation. This factor is also not considered in the estimation procedure.

The southern region has minimum error of estimation since this region is characterized by the stable weather and cloud free skies.

3.2. *Comparison between the current modified formula (2) and El-Shahawy's formula (7)*

El-Shahawy, 1984 proposed a semi-empirical formula for estimating the global solar radiation, H, in Egypt as follows;

$$H = A\ \overline{Q}[1+2\alpha f)(1-\sin(\varphi\text{-}\delta)-fh]\ \text{cal.cm}^{-2}\text{day}^{-1} \quad (7)$$

Where $\overline{Q}$ is the mean daily values of cloudiness coefficient, $A = J_o\, d/h$, J_o, is the solar constant (J_o is taken here as 1396 Wm^{-2}), d = $8\cos^{-1}(-\tan\varphi\tan\delta)$ minutes, $h = (\pi/2+\delta-\alpha)$ radians, δ is the sun declination and α is the surface albedo, ϕ is the latitude and $f = \sin(0.2\delta)+0.1$.

El-Shahawy used his formula to estimate the monthly mean global solar radiation for the year 1978 at four selected stations in Egypt namely Matruh, Tahrir, Bahtim and El-Kharga. His results are given in Table 4 where he compared his results with the corresponding measured values, H_m, at Matruh and El-Kharga. He found good agreement between the estimated and measured values of global radiation.

In the present study, the previous results of El-Shahawy formula (7) have been compared with the corresponding estimated values applying the current modified formula (2) to show the merits of the two formulae. Therefore, The corresponding values of global solar radiation have been estimated for the same year 1978 at the two stations of Matruh and El-Kharga using their recorded data of sunshine hours, n, and the values of the parameter K with applying the modified formula (2). The records of n values have been obtained from the Egyptian Meteorological Authority while K values for the both stations are taken from Table 2. Tahrir and Bahtim are excepted from this comparison because the data of sunshine hours, n, are not recorded at them for the study year, 1978. On the other hand, Matruh and El-Kharga are found appropriate for the comparison purposes. Matruh is a coast city and characterized by highest cloud cover in a year while El-Kharga is a desert city and characterized by clear atmosphere and stable weather conditions. In

TABLE 4

Measured, H_m, and estimated values, H_{cH}, of the monthly mean global solar radiation for the year 1978 and their percentage errors, e_H, at Matruh and El-Kharga stations applying formula (7), cited from El-Shahawy (1998) in addition to the corresponding estimated values, H_{cB}, using the current formula (2) and their percentage errors, e_B

Month	Station									
	Matruh					El-Kharga				
	H_m	H_{cH}	H_{cB}	e_H	e_B	H_m	H_{cH}	H_{cB}	e_H	e_B
Jan	09.7	08.9	10.6	8.2	-9.3	17.5	16.6	18.3	5.1	-4.6
Feb	13.5	12.9	14.2	4.4	-5.2	21.5	20.7	22.3	3.7	-3.7
Mar	17.4	18.2	16.7	-4.6	4.0	24.8	25.0	24.6	-1.8	0.8
Apr	20.7	21.7	20.1	-4.8	2.9	27.9	29.0	27.6	-3.9	1.1
May	23.6	24.1	23.2	-2.1	1.7	30.6	31.1	30.2	-1.6	1.3
Jun	25.5	25.7	25.4	-0.8	0.4	31.8	31.9	31.7	-0.3	0.3
Jul	24.8	25.2	24.5	-1.6	1.2	30.3	30.8	29.7	-1.7	2.0
Aug	22.6	23.1	22.3	-2.2	1.3	29.9	30.0	29.7	-0.3	0.7
Sep	20.4	21.4	20.2	-4.9	0.6	27.1	28.2	26.1	-4.1	3.7
Oct\	17.1	17.8	17.0	-4.1	1.0	21.7	21.8	21.4	-0.5	1.4
Nov	12.6	12.3	13.2	2.4	-4.8	19.2	17.6	20.0	8.3	-4.2
Dec	09.2	08.8	09.8	4.3	-6.5	*	14.1	—	—	—

* H_m is not recorded

addition, El-Shahawy's formula concerned with cloud amounts and types as mentioned above. The obtained results are also given in Table 4 with El-Shahawy's results.

The following results could be clearly seen from Table 4:

(*i*) e_B at Matruh is higher than e_H during cold winter season (From November to February) while the opposite occurs during remaining months. This is attributed to higher cloud cover and its effects during winter season than during remain year months. The cloud effects are not taken in the consideration with respect to the formula (2).

(*ii*) At both selected stations, El-Shahawy's formula (7) is underestimating during cold winter season (From November to February) and overestimating during remaining months and *vise versa* with respect to the formula (2). The accumulation of observation errors of cloud types and amounts partially explain the underestimation of El-Shahawy's formula during winter season. On the other hand, the overestimation of El-Shahawy's formula during remain months could be attributed to the solar constant which has been taken as 1396 Wm^{-2} in his computations while ISO and WMO have accepted a value of 1369±7 Wm^{-2}.

(*iii*) e_H at Matruh is higher than e_B at El-Kharga during most year months especially during cold winter season. This is due to, as mentioned above, Matruh is coast city and characterized by highest cloud cover during most of the year especially in winter months while El-Kharga is characterized by clear atmosphere and stable weather conditions.

(*iv*) The possible error of the annual mean of estimated values at Matruh applying the current formula (2) is very small if compared with its corresponding value of El-Shahawy's formula, ($e_B = -0.055$ while $e_H = -1.38$). This means that the formula (2) gives better estimations for global radiation as the annual average than El-Shahawy formula.

From the above discussion, it could be concluded that the above both two formulae are valid to compute global solar radiation with high accuracy at any locality in Egypt during all year months. However, the current modified formula is characterized by simplicity and independence of meteorological parameters, which in turn precisely estimates solar radiation at any locality in Egypt during all months despite relatively higher computation errors during winter cloudy months. On the contrary, the accumulation of observation errors of cloud types and amounts and other input data could lead to higher computation errors of El-Shahawy's formula (7) beside the obtaining these input data require establishing meteorological stations which cost exorbitantly.

TABLE 5

Values of regression and correlation coefficients of equation (10) and the standard mean error for the selected stations and the corresponding regions

Region & station	a		b		*R*		*E*	
	Local	region	Local	region	Local	Region	Local	region
Region 1								
Sidi-Barrani	0.7983		-0.5566		0.9687		0.0016	
Matruh	0.7279	0.8033	-0.4586	-0.5383	0.9662	0.8961	0.0030	0.0322
El-Arich	0.8671		-0.6052		0.9716		0.0042	
Region 2								
Tahrir	0.8262	0.8037	-0.5951	-0.5778	0.9634	0.9389	0.0432	0.0143
Cairo	0.8076		-0.5963		0.9839		0.0017	
Region 3								
El-Kharga	0.5913	0.5913	-0.3556	-0.3556	0.9644	0.9644	0.0062	0.0062
Region 5								
Aswan	0.4394	0.4394	-0.1794	-0.1794	0.9690	0.9690	0.0083	0.0083
All Egypt	0.8413		-0.6191		0.8751		0.0314	

3.3. *Computation of diffuse solar radiation*

The above data of measured global radiation H_m, and sunshine hours n, in addition to the corresponding values of measured diffuse radiation D_m, for the same period (1985 to 1989) have been used to relate the values of the fraction of diffuse solar radiation (D_m /H_m) with the corresponding values of n/N for the selected stations. Bahtim and Asyut are excepted from this study as measurements of diffuse radiation are not available at these places (Table 1).

The mean daily number of hours of daylight (N) between sunrise and sunset are calculated using Cooper's formula 1969;

$$N = (2/15) \cos^{-1} [(-\tan \varphi) (\tan \delta)] \qquad (8)$$

Where φ is the latitude (in degree) and δ is the solar declination angle;

$$\delta = 23.45 \sin [360(284 + n')/365] \qquad (9)$$

The obtained relation is linear. It could be written as follows;

$$D_m/H_m = a + b(n/N) \qquad (10)$$

where a and b are the regression coefficients. Their values in addition to the correlation coefficients R, and the standard mean errors E, are given in the following Table 5.

The monthly mean values of diffuse solar radiation have been estimated for the year 1995 at each station using the corresponding measured values of H_m and n/N for the same year and applying equation (10) with the regression coefficients, a and b, from Table 5 for each station. The used data of H_m are given above in Table 3. The values of n/N are presented in Table 6 with the obtained calculated values of diffuse solar radiation, D_c, where the verification has been performed through a comparison between the estimated and measured values.

The agreement between measured and estimated values is remarkable. The method of estimation is fluctuated between small overestimation and underestimation at all stations during all the months. The maximum error occurs during the hot months from March to July at all stations. This is due to the occurrence of Khamsin depressions in the north and the effect of Sudan monsoon low in the south during the mentioned months. This factor is not considered in the estimation procedure. The maximum error is 7.6% at Sidi-Barrani, 7.52% at El-Arich, 7.64% at Matruh, 6.34% at Tahrir, 6.99% at Cairo, 5.93% at El-Kharga and 6.5% at Aswan.

It is noticed, from Table 6, that the possible error of estimated values, e, at Sidi-Barrani is lower than those the other two stations of regional 1, Matruh and El-Arich, during winter months despite the fact that their skies become more cloudy due to invasion of extratropical system in winter from the north. This is due to relatively lower winter clouds cover over Sidi-Barrani than those at Matruh and El-Arich during the year of 1995. It is also noticed that, the values of D_m show gradual increase as we go eastward from Matruh to El-Arich. This is attributed to the corresponding gradual increase in cloud cover from west to east.

TABLE 6

The values of *n/N* and the estimated diffuse radiation, D_c, compared with the measured values, D_m, with their percentage error, *e*, at different stations

Region & station		J	F	M	A	M	J	J	A	S	O	N	D
Region 1													
	n/N	0.65	0.66	0.71	0.71	0.71	0.83	0.89	0.89	0.85	0.84	0.71	0.65
	D_c	4.71	5.86	7.90	9.23	10.1	9.45	8.75	8.18	7.67	6.15	5.16	4.54
Sidi-Barrani	D_m	4.74	5.93	7.86	9.50	9.64	8.78	8.96	8.08	7.82	6.24	5.19	4.67
	e	0.63	1.18	-0.5	2.84	-4.8	-7.6	2.34	-1.2	1.92	1.44	0.58	2.78
	n/N	0.66	0.63	0.72	0.74	0.83	0.90	0.87	0.83	0.77	0.76	0.68	0.61
	D_c	5.05	6.80	8.54	9.85	9.34	9.58	9.67	9.48	9.06	6.84	5.83	4.98
El-Arich	D_m	4.79	6.64	8.87	9.70	10.1	9.92	9.43	8.99	9.22	6.95	6.06	4.72
	e	-5.4	-2.4	3.72	-1.5	7.52	3.43	-2.6	-5.5	1.74	1.58	3.8	-5.5
	n/N	0.66	0.70	0.69	0.70	0.81	0.91	0.93	0.89	0.84	0.84	0.72	0.60
Matruh	D_c	4.42	5.70	8.02	9.40	9.59	9.22	8.95	8.57	7.98	6.10	5.17	4.44
	D_m	4.16	5.80	8.19	9.14	9.96	9.32	9.69	8.59	7.98	6.28	5.06	4.31
	e	-6.2	1.72	2.08	-2.8	3.71	1.07	7.64	0.23	0.00	2.87	-2.2	-3.0
Region 2													
	n/N	0.70	0.65	0.70	0.75	0.74	0.87	0.87	0.85	0.84	0.77	0.68	0.62
Tahrir	D_c	4.67	6.20	8.27	9.50	9.99	9.22	8.82	8.55	8.06	6.55	5.56	4.66
	D_m	4.79	6.06	8.83	9.70	9.69	9.02	8.60	8.35	8.13	6.47	5.31	4.55
	e	2.51	-2.3	6.34	2.06	-3.1	-2.2	-2.6	-2.4	0.86	-1.2	-4.7	-2.4
	n/N	0.65	0.64	0.73	0.77	0.75	0.85	0.86	0.77	0.76	0.76	0.64	0.55
Cairo	D_c	4.28	5.67	7.19	7.98	8.65	8.39	8.05	8.71	7.73	5.74	5.28	4.65
	D_m	4.50	5.9	7.60	8.3	9.3	9.0	8.5	8.4	8.1	6.1	5.6	4.6
	e	4.89	3.9	5.39	3.86	6.99	6.78	5.29	-3.7	4.57	5.9	5.71	-1.1
Region 3													
	n/N	0.89	0.86	0.81	0.86	0.82	0.90	0.88	0.92	0.89	0.87	0.89	0.80
El-Kharga	D_c	4.34	5.25	6.98	7.97	8.54	8.38	8.41	7.71	7.45	5.75	4.64	4.23
	D_m	4.50	5.44	7.42	8.29	8.65	8.20	7.81	7.78	7.89	5.61	4.59	4.20
	e	3.56	3.49	5.93	3.86	1.27	-2.2	-7.7	0.9	5.58	-2.5	-1.1	-0.7
Region 4													
	n/N	0.95	0.92	0.84	0.86	0.88	0.91	0.93	0.90	0.86	0.85	0.85	0.86
Aswan	D_c	4.90	5.87	7.42	8.07	8.05	8.51	8.34	8.23	7.84	6.14	5.19	4.48
	D_m	4.78	5.64	7.20	7.96	8.61	8.90	8.11	8.12	7.67	6.21	5.33	4.41
	e	-2.5	-4.1	-3.1	-1.4	6.5	4.38	-2.8	-1.4	-2.2	1.13	2.63	-1.6

3.4. *Annual variation of radiation components over Egypt*

The characteristics of the annual variation of the monthly mean daily values of measured global, H_m, and diffuse solar radiation, D_m for the year 1995 over the five regions have been examined. El-Arich and Cairo have been chosen to represent region 1 and region 2 respectively, while remaining regions represented by the other three stations as in Table 2. The monthly mean values of , H_m, and D_m, for the five stations, El-Arich, Cairo, El-Kharga, Asyut and Aswan are illustrated in Fig. 1&2 respectively. Asyut has been excluded from Fig. 2 because D_m is not measured there.

3.4. (a). *Global solar radiation*

It could be clearly seen that Cairo has the lowest value of H_m, of all stations over a year. This could be attributed to the urbanization of the area characterized by highly polluted air, which leads to loss in the incident energy of solar beam due to backscattering and absorption.

Also, it is noticed that the values of H_m, at El-Arich are marginally higher than Cairo's values but lower than the values of the other three stations over the year. This is because El-Arich is a coastal station and characterized by high amount of cloud cover and water vapor content. The

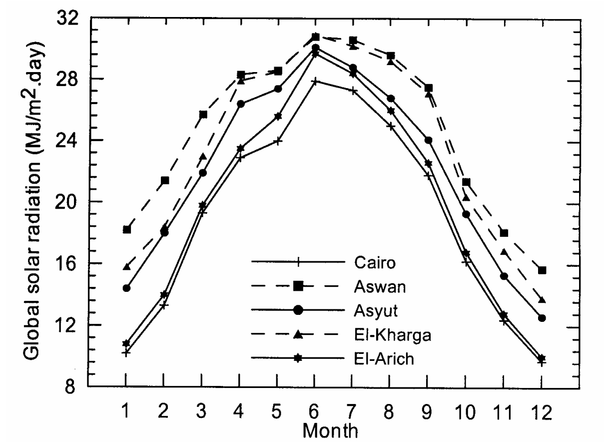

Fig. 1. Annual variation of global solar radiation, H_m, at different stations

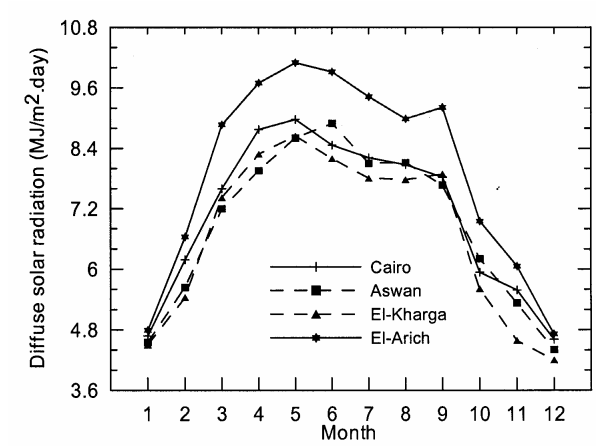

Fig. 2. Annual variation of diffuse solar radiation, D_m, at different stations

difference between the H_m, values of Cairo and El-Arich is high in summer season as compared with winter season. This may be attributed to neglected effect of cloud cover and moisture phenomena during hot summer season over El-Arich due to the maximum atmospheric heating. The comparison between global radiation at Cairo and El-Arich shows clearly that, the effect of polluted air and aerosols on reduction of global solar radiation is approximately equivalent the effect of clouds and water vapor content.

Aswan has the highest value of H_m, of all the stations over the year. This is mainly due to Aswan's clear atmosphere and stable weather through most of the year. Also, the values of H_m, at both stations of El-Kharga and Asyut are high when compared to the values of Cairo and El-Arich. This is also due to clear atmosphere and stable weather conditions at El-Kharga and Asyut as compared to Cairo and El-Arich.

On the other hand, there is a strong latitudinal gradient for global solar radiation in winter compared to that of summer. This is due to the invasion of extratropical systems in winter from north passing over the Mediterranean Sea providing an increased cloud cover over northern Egypt. The summer season is influenced by a high-pressure cell, which is characterized by stable and clear sky weather adding to increased values of global radiation. All stations reach maximum in June and have continued higher H_m, during July as well.

3.4. (b). *Diffuse solar radiation*

Since diffuse solar radiation is largely influenced by cloud cover and atmospheric turbidity, it attains its distinct highest values at El-Arich. This is attributed to, as mentioned above, the effect of high amount of cloud cover and water vapor content of El-Arich. On the other hand, Cairo has higher values of D_m, compared to El-Kharga and Aswan. This indicates that Cairo is turbid atmosphere and equivalent over the year. It is also noticed that El-Kharga has the lowest values of D_m, during the period from June to December, except in September month. This indicates domination of clear sky condition at El-Kharga. Although Aswan is characterized by stable atmospheric conditions like El-Kharga, it has relatively higher values of D_m, than those of El-Kharga during most months. This is due to Aswan's geographical location beside the River Nile, which in turn cause relatively higher atmospheric humidity and water vapor than those are over El-Kharga, which lies in the western desert. It is interesting to note that D_m, reaches maximum in May at all places except at Aswan where it is in June.

4. Conclusion

The investigated area of Egypt has been divided into five regions represent most the country and represented by the nine selected stations while the year has been divided into cold season (October to February) and hot season (March to September). The provided data of sunshine hours, *n*, global solar radiation, *H*, have been analyzed using an advanced computer program to obtain an appropriate regional parameter *K*, of an empirical relation, (equation 2) of Barbaro *et al*. for each region. The obtained results are given in Table 2. The agreement between measured and estimated values is remarkable. The maximum possible error of estimated values do not exceed 9.6%. This points to the high potential of the proposed regional parameters *K* in equation (2) for practical applications. The current modified formula (2) gives better estimations for global solar radiation at any locality in Egypt. Relation between the diffuse fraction *D/H* and the relative duration of sunshine (*n/N*) is also determined for each region and its represented stations. The Regression coefficients and the relative percentage error are given in Table 5. Diffuse irradiation, *D*, could be estimated with maximum error 7.7%. A comparative study for the global and diffuse solar radiation over different sites has been investigated. The study shows clearly the effect of urban air of Cairo on the reduction of global radiation and the effect of cloud and moisture phenomenon on the increase of diffuse radiation at coastal area of El-Arich.

The used data of the monthly mean daily values of *n*, *H* and *D* of the five years (1985 to 1989) for the nine stations that measure radiation in Egypt have been obtained from the Egyptian Meteorological Authority.

In conclusion, this study provides methods for estimating global and diffuse solar radiation as well as direct solar radiation with high accuracy at any location in Egypt. This is useful for the design of various systems utilizing solar energy.

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