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Analysis of solar radiation over Egypt

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With 9 Figures

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Summary

The database utilized in this analysis consisted of daily sunshine duration and hourly global and diffuse radiation on a horizontal surface (for Matruh Cairo, and Aswan), and normal incidence beam radiation (for Cairo and Aswan only). Monthly-average hourly and daily values are reported for each of these three types of measured radiation, together with the calculated monthly-average daily values for the components of global radiation, horizontal beam and diffuse radiation. The monthly-average hourly and daily clearsky index values have also been calculated and analyzed. Monthly-average daily frequency distributions of the clearsky index values are reported for each month.

The annual-average daily global irradiation values are 19.4, 18.67, and 21.78 MJ/m^2 and for diffuse irradiation they are 6.34, 6.65 and 6.23 MJ/m^2 for Matruh, Cairo and Aswan, respectively. For the normal incidence beam irradiation the annual-average daily values are 16.94 and 24.46 MJ/m^2 for Cairo and Aswan, respectively. The annual-average daily fractions of the direct component of horizontal global radiation are 0.70, 0.61 and 0.72 for the three stations, respectively. The annual-average daily values for the clearsky index are 0.585, 0.566, and 0.648, and the average frequency of clear days annually are 67.3, 42.3 and 77.6% respectively.

The annual variations and trend analysis were analyzed for daily global, direct, and diffuse radiation on a horizontal surface, daily sunshine duration, and for the daily ratios G/G_0, and D/G for the stations Matruh, Cairo and Aswan. The distribution of these components of radiation and their ratios over the study stations in Egypt is also discussed.

The results show that Egypt is characterized by relatively high average-daily radiation rates, both global and direct, and a relatively high frequency of clear days. Cairo, due to its urbanization and high pollution, has relatively low average-daily radiation rates, particularly in direct radiation, and the frequency of clear days.

Nomenclature

D	Monthly average daily diffuse irradiation in MJ/m^2
G, G_0	Monthly average daily global and extraterrestrial irradiation in MJ/m^2
S	Monthly average daily sunshine duration in hours
I_N	Normal incidence beam irradiation in MJ/m^2
I_H	Direct irradiation incident on a horizontal surface in MJ/m^2
G/G_0	Clearness index
D/G	Diffuse fraction

1. Introduction

The knowledge of solar radiation climate of an area is important for assessing the potential use of solar energy to be converted to either thermal or electrical energy, as a power source. Such information is a prerequisite for the design of solar energy conversion systems.

El-Hussainy (1992) presented and discussed some climatic features of surface radiation components over Egypt. He found that the global solar radiation over Egypt declined by 0.7% yr^{-1}, due to the natural increase in cloud amount, volcanic effects, and anthropogenic effects. Kudishi et al. (1992) introduced an important analysis of solar radiation data for Beer Sheva, Israel, and they concluded that this location is characterized by relatively high average-daily radiation rates, both global and direct, and with relatively high frequency of clear days. El-Hussainy (1995) presented monthly maps for global, diffuse and direct solar radiation over Egypt. He found that the area-time average of diffuse irradiance over Egypt would lie somewhere between 6 and 8 MJ m^{-2} day^{-1}, whereas it is between 18 and 24 MJ m^{-2} day^{-1} for global irradiance.

The aim of this work is to long records of hourly measurements of analyse global and diffuse radiation on horizontal surface and normal incidence radiation for three different types of stations, Matruh (coastal), Cairo (urban) and Aswan (low latitude). An analysis is also made of the monthly average daily values of the radiation parameters for all the stations in the Egyptian network. A comparison is also made between the results presented for the Egyptian stations in this study and the results presented by Kudiish et al. (1992) for Beer Sheva, Israel.

2. Main features of the climate of Egypt

2.1 Cloud characteristics and atmospheric transparency change markedly from one season to the other

(a) In winter, conditions of middle latitude disturbances are prevalent where cloud types are normally opaque to the direct beam and the turbidity of the atmosphere is low.
(b) Spring is characterized by the passage of small and shallow thermal disturbances, including what is called "Khamsin weather". With the onset of such thermal lows, vertical visibility deteriorates progressively with increasing dust content in the lower layers of the atmosphere. Occasionally, this is accompanied with stratified cloud types that proceed from high transparent cirrus type to medium opaque alto- and nimbo-stratus clouds. After the passage of the disturbance, cumuliform clouds and low turbidity prevail.
(c) In summer, high and semi transparent clouds prevail, with a dirty sky most of the time, due to a deep layer of fine dust particles associated with continental tropical air. The dust content falls markedly when Mediterranean air arrives, with associated fine weather cumulus developing.
(d) In autumn, the atmosphere is moderately transparent on average. Morning mists and low clouds form but generally dissipate after sunrise.

2.2 There is a marked variation in climatic regime from north to south

(a) The north strip – several kilometers wide – does not enjoy the succession of seasonal regimes described above in a clear cut manner. As can be expected, Cu-cloud types varying in thickness, cover, and frequency prevail all the year round. Clear air is the rule and dust-laden air is only the exception.
(b) To the south, the continental tropical patterns manifest themselves more and more. In the extreme south the extra-tropical regime does not appear except in midwinter. The rate of variation is greatest in the north and falls markedly at two to three hundred kilometers to the south so that southern-Egypt can almost be considered as one climatic zone.

3. Measurements

The Radiation network of stations in Egypt consists of ten stations (Fig. 1, Table 1). It started measuring global radiation in 1969 at four stations using Eppley pyranometers with Speedomax recorder. In the beginning of 1980, the system was connected to digital integrators (CJ10), and the values of measurements were corrected from

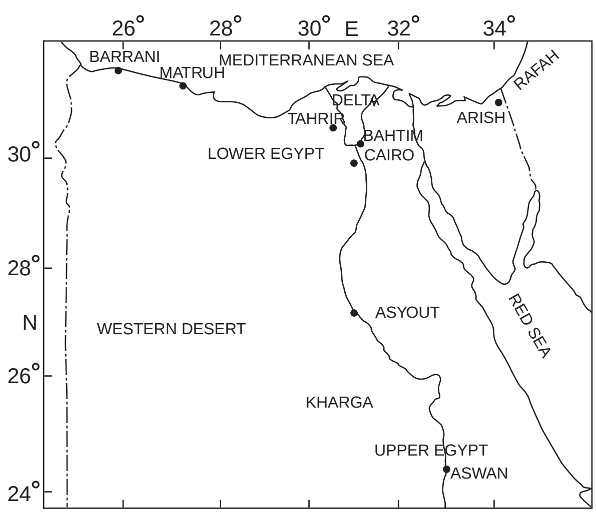

Fig. 1. Radiation network stations in Egypt

Table 1. Egyptian network stations

Stn No	Name	Lat.	Lon.	Elevation	I_N	G	D
301	S. Barrani	31° 17′N	25° 54′E	23.7 m	–	08/85	08/85
306	Matruh	31 20′N	27 13′E	25.0	–	07/81	07/81
335	Rafah	31 18′N	34 42′E	75.0	–	12/90	12/90
337	El-Arish	31 52′N	33 30′E	30.6	–	12/85	12/85
345	Tahrir	30 39′N	30 42′E	15.6	–	01/69	08/81
369	Bahtim	30 08′N	31 15′E	17.9	–	01/69	–
371	Cairo	30 05′N	31 17′E	34.4	01/80	01/69	07/74
392	Asyout	27 12′N	31 10′E	52.0	–	01/81	–
414	Aswan	25 58′N	32 47′E	192.7	11/88	01/80	12/81
435	El-Hharga	25 27′N	30 32′E	77.8	–	08/71	09/81

the International Pyrheliometric scale 1956 (IPS 56) to the World Radio Radiometric Reference (WRR). The measurements of diffuse radiation started at Cairo H.Q. 1975, using Eppley pyranometers with shadow rings. The measurements of direct solar radiation started in 1977, using Eppley normal incidence pyrheliometers (NIP).

The pyranometers are calibrated against a reference pyranometer, which is calibrated against a standard pyrheliometer. This standard pyrheliometer is periodically calibrated every five years at the World Radiation Center (WRC) in Davos, Switzerland. The errors involved in the radiation measurements are assumed to be around 1.5% for normal incidence radiation and 2.5% for global radiation.

The available hourly global and diffuse radiations data analyzed in this study were collected during the time interval 1980–1994 for three stations; Matruh, Cairo and Aswan. The available hourly normale in incidence beam irradiation data refers to the time interval 1980–1994 for Cairo and Aswan only. The daily direct solar radiation on horizontal surface used for Matruh is calculated from the relation ($I_H = G - D$). The years 87, and 91 are not available in this data series. Another set of data comprised of the monthly average daily values for the radiation components and sunshine duration for the whole periods shown in Table 1 is used for the analysis of annual variations and trend for the complete network of stations.

4. Results

A solar constant value of 1376 W/m^2 is adopted as recommended by Davies et al. (1988). Astronomical parameters are calculated through the normal equations and following Spencer (1971). Results of the analysis of our three sets of solar radiation

Table 2a. Monthly-average hourly and daily NIP irradiation for Cairo

Mo	Days	5–6	6–7	–8	–9	–10	–11	–12	–13	–14	–15	–16	–17	–18	–19	Av day
Jan	434	.00	.00	0.36	0.98	1.40	1.63	1.63	1.57	1.48	1.31	0.96	0.43	0.16	.00	11.11
Feb	367	.00	.03	0.64	1.15	1.55	1.71	1.71	1.62	1.53	1.34	1.13	0.69	0.14	.00	12.46
Mar	403	.02	.27	0.89	1.34	1.73	1.91	1.97	1.89	1.83	1.63	1.36	0.97	0.34	.00	15.31
Apr	390	.01	.58	1.08	1.47	1.86	2.06	2.14	2.10	1.99	1.81	1.47	1.07	0.44	.02	17.63
May	403	.15	.84	1.33	1.75	2.08	2.21	2.25	2.18	2.07	1.93	1.62	1.24	0.63	.07	19.77
Jun	390	.22	.92	1.49	2.01	2.37	2.53	2.61	2.56	2.48	2.28	1.99	1.58	0.94	.18	23.71
Jul	434	.16	.70	1.19	1.72	2.19	2.43	2.56	2.59	2.54	2.39	2.13	1.71	1.04	.20	23.15
Aug	434	.03	.49	1.01	1.51	2.06	2.36	2.50	2.53	2.48	2.30	1.99	1.54	0.75	.06	21.29
Sep	419	.01	.44	1.02	1.51	1.97	2.26	2.39	2.38	2.30	2.05	1.68	1.06	0.27	.02	18.81
Oct	434	.00	.31	1.01	1.50	1.90	2.06	2.16	2.14	1.99	1.71	1.26	0.52	0.02	.00	16.26
Nov	420	.00	.10	0.74	1.20	1.65	1.79	1.82	1.72	1.62	1.40	0.92	0.23	0.01	.00	12.74
Dec	433	.00	.01	0.46	1.01	1.46	1.66	1.72	1.62	1.49	1.29	0.87	0.24	0.24	.00	11.07
Yr		.12	.52	0.96	1.44	1.85	2.05	2.13	2.08	1.99	1.79	1.46	0.99	0.57	.12	16.94

Table 2b. Monthly-average hourly and daily NIP irradiation for Aswan

Mo	Days	5–6	6–7	–8	–9	–10	–11	–12	–13	–14	–15	–16	–17	–18	–19	Av day
Jan	155	.00	0.11	1.29	2.17	2.59	2.77	2.86	2.86	2.79	2.57	2.20	1.32	0.12	.00	23.41
Feb	141	.00	0.29	1.64	2.45	2.84	3.04	3.13	3.12	3.06	2.89	2.56	1.89	0.46	.00	27.33
Mar	154	.02	0.68	1.81	2.44	2.68	2.82	2.85	2.87	2.75	2.56	2.25	1.74	0.63	.02	25.59
Apr	150	.08	0.94	1.76	2.21	2.44	2.58	2.59	2.57	2.44	2.28	1.96	1.52	0.60	.05	23.13
May	155	.27	1.24	1.84	2.18	2.40	2.47	2.54	2.47	2.35	2.18	1.96	1.53	0.81	.06	22.92
Jun	149	.49	1.62	2.30	2.59	2.85	2.97	3.05	3.03	2.94	2.79	2.56	2.12	1.29	.20	28.34
Jul	155	.28	1.33	2.05	2.48	2.67	2.79	2.84	2.77	2.77	2.66	2.40	1.97	1.22	.19	26.87
Aug	159	.16	1.25	2.07	2.46	2.66	2.82	2.87	2.85	2.75	2.62	2.40	1.89	0.93	.06	25.69
Sep	150	.07	1.07	1.97	2.43	2.67	2.82	2.87	2.86	2.77	2.59	2.25	1.66	0.52	.00	24.09
Oct	155	.02	0.81	1.86	2.39	2.67	2.84	2.87	2.86	2.70	2.48	2.00	1.04	0.06	.00	23.17
Nov	150	.01	0.66	1.97	2.56	2.83	2.97	3.03	2.99	2.88	2.60	2.06	0.91	0.01	.00	24.53
Dec	155	.00	0.25	1.54	2.33	2.66	2.80	2.84	2.86	2.82	2.58	2.14	0.95	0.00	.00	22.83
Yr		.20	0.85	1.83	2.39	2.66	2.80	2.86	2.84	2.75	2.56	2.22	1.54	0.63	.12	24.46

Table 3a. Monthly-average hourly and daily global irradiation for Matruh

Mo	Days	5–6	6–7	–8	–9	–10	–11	–12	–13	–14	–15	–16	–17	–18	–19	Av day
Jan	309	.00	.00	0.13	0.50	0.99	1.41	1.64	1.72	1.58	1.28	0.82	0.33	.03	.00	10.17
Feb	282	.00	.01	0.24	0.77	1.35	1.83	2.19	2.25	2.11	1.76	1.28	0.70	.16	.00	13.91
Mar	278	.00	.08	0.52	1.18	1.84	2.35	2.66	2.77	2.59	2.20	1.63	0.97	.32	.01	18.94
Apr	297	.02	.32	0.97	1.71	2.38	2.88	3.18	3.24	3.04	2.62	1.95	1.24	.53	.06	22.21
May	341	.09	.56	1.24	2.02	2.67	3.14	3.38	3.42	3.22	2.79	2.16	1.41	.69	.16	25.33
Jun	300	.13	.70	1.36	2.11	2.76	3.23	3.52	3.55	3.38	2.99	2.41	1.60	.85	.27	25.83
Jul	372	.08	.55	1.28	2.03	2.73	3.26	3.53	3.62	3.47	3.09	2.46	1.65	.87	.28	27.64
Aug	372	.02	.39	1.10	1.86	2.59	3.11	3.43	3.49	3.32	2.92	2.28	1.48	.75	.13	25.61
Sep	362	.00	.26	0.89	1.64	2.31	2.86	3.15	3.16	2.94	2.46	1.81	1.06	.33	.05	21.60
Oct	372	.00	.15	0.70	1.36	1.96	2.36	2.59	2.62	2.35	1.89	1.25	0.62	.09	.01	15.87
Nov	299	.00	.08	0.37	0.93	1.48	1.86	2.03	2.03	1.78	1.35	0.81	0.27	.05	.00	13.10
Dec	341	.00	.02	0.16	0.60	1.13	1.53	1.71	1.71	1.48	1.16	0.69	0.22	.01	.00	09.97
Yr		.07	.31	0.76	1.41	2.03	2.50	2.77	2.82	2.62	2.22	1.64	0.97	.42	.15	19.40

Table 3b. Monthly-average hourly and daily global irradiation for Cairo

Mo	Days	5–6	6–7	–8	–9	–10	–11	–12	–13	–14	–15	–16	–17	–18	–19	Av day
Jan	372	.00	.00	0.19	0.64	1.16	1.57	1.74	1.73	1.50	1.17	0.69	0.23	.01	.00	10.63
Feb	339	.00	.02	0.33	0.86	1.42	1.88	2.06	2.02	1.82	1.45	0.98	0.45	.06	.00	13.34
Mar	372	.00	.14	0.65	1.32	1.91	2.37	2.64	2.60	2.39	1.95	1.37	0.73	.17	.00	18.22
Apr	360	.04	.40	1.03	1.73	2.35	2.81	3.06	3.01	2.74	2.25	1.60	0.92	.30	.01	22.25
May	372	.14	.63	1.31	2.01	2.64	3.05	3.23	3.16	2.89	2.43	1.80	1.09	.45	.05	24.84
Jun	360	.17	.69	1.40	2.13	2.75	3.19	3.41	3.38	3.13	2.66	2.03	1.31	.61	.11	26.83
Jul	403	.11	.55	1.21	1.95	2.62	3.09	3.35	3.36	3.14	2.68	2.05	1.33	.63	.11	26.15
Aug	403	.04	.40	1.03	1.75	2.46	2.95	3.21	3.21	2.98	2.50	1.84	1.12	.42	.04	23.93
Sep	390	.01	.29	0.90	1.60	2.26	2.73	2.95	2.90	2.63	2.09	1.43	0.71	.15	.00	20.30
Oct	372	.00	.18	0.71	1.34	1.91	2.30	2.47	2.39	2.08	1.56	0.93	0.32	.02	.00	15.59
Nov	390	.00	.06	0.44	0.94	1.46	1.81	1.94	1.83	1.55	1.14	0.59	0.13	.00	.00	11.79
Dec	403	.00	.01	0.23	0.68	1.15	1.51	1.70	1.64	1.41	1.02	0.53	0.11	.00	.00	09.98
Yr		.08	.29	0.79	1.41	2.01	2.44	2.65	2.61	2.35	1.91	1.32	0.71	.30	.06	18.67

Table 3c. Monthly-average hourly and daily global irradiation for Aswan

Mo	Days	5–6	6–7	–8	–9	–10	–11	–12	–13	–14	–15	–16	–17	–18	–19	Av day
Jan	341	.00	.04	0.46	1.15	1.79	2.25	2.49	2.46	2.21	1.74	1.10	0.41	.02	.00	16.07
Feb	311	.00	.08	0.63	1.39	2.09	2.59	2.86	2.87	2.61	2.11	1.45	0.69	.10	.00	19.37
Mar	341	.01	.25	0.96	1.77	2.45	2.92	3.23	3.19	2.89	2.37	1.66	0.87	.19	.00	22.78
Apr	329	.05	.53	1.33	2.12	2.77	3.22	3.43	3.37	3.05	2.51	1.78	1.02	.27	.00	25.28
May	341	.13	.71	1.45	2.18	2.76	3.15	3.35	3.26	2.97	2.45	1.77	1.04	.36	.02	25.31
Jun	330	.17	.78	1.54	2.27	2.86	3.27	3.49	3.44	3.14	2.66	2.06	1.23	.50	.04	27.17
Jul	372	.11	.68	1.44	2.17	2.80	3.24	3.45	3.43	3.17	2.68	2.02	1.26	.53	.05	26.53
Aug	372	.07	.57	1.33	2.11	2.75	3.20	3.41	3.38	3.09	2.58	1.89	1.10	.37	.01	25.50
Sep	360	.03	.45	1.20	1.97	2.60	3.02	3.21	3.13	2.82	2.26	1.54	0.77	.13	.00	23.01
Oct	372	.01	.34	1.05	1.79	2.39	2.78	2.91	2.80	2.42	1.85	1.13	0.40	.02	.00	19.42
Nov	360	.00	.18	0.82	1.51	2.08	2.47	2.60	2.49	2.14	1.58	0.89	0.23	.02	.00	16.60
Dec	370	.00	.07	0.55	1.23	1.80	2.20	2.37	2.30	2.00	1.48	0.84	0.22	.01	.00	14.69
Yr		.07	.39	1.07	1.80	2.43	2.86	3.07	3.01	2.71	2.19	1.51	0.77	.25	.03	21.78

Table 4a. Monthly-average hourly and daily diffuse irradiation for Matruh

Mo	Days	5–6	6–7	–8	–9	–10	–11	–12	–13	–14	–15	–16	–17	–18	–19	Av day
Jan	309	.00	.00	.07	.27	.44	0.58	0.68	0.71	0.65	0.57	.41	.21	.03	.00	4.47
Feb	280	.00	.01	.15	.38	.59	0.77	0.87	0.90	0.87	0.76	.58	.35	.11	.00	6.11
Mar	309	.01	.09	.37	.64	.85	1.02	1.08	1.07	1.02	0.90	.74	.51	.23	.02	8.34
Apr	270	.02	.25	.56	.81	.96	1.06	1.15	1.17	1.11	0.99	.82	.62	.34	.06	9.46
May	278	.09	.39	.65	.86	.99	1.05	1.10	1.06	1.02	0.93	.81	.64	.43	.14	8.25
Jun	269	.12	.41	.62	.75	.85	0.89	0.95	0.99	0.98	0.88	.76	.63	.46	.22	7.30
Jul	341	.08	.34	.55	.68	.75	0.77	0.81	0.79	0.79	0.72	.68	.58	.46	.22	6.77
Aug	341	.02	.26	.51	.67	.75	0.77	0.78	0.78	0.77	0.73	.65	.54	.37	.12	6.47
Sep	360	.01	.17	.44	.63	.75	0.78	0.78	0.77	0.74	0.68	.58	.43	.20	.02	5.95
Oct	372	.00	.08	.33	.53	.66	0.74	0.76	0.73	0.70	0.61	.47	.28	.05	.00	5.6
Nov	360	.00	.02	.21	.42	.58	0.70	0.75	0.73	0.66	0.55	.39	.17	.01	.00	5.00
Dec	371	.00	.00	.10	.29	.45	0.54	0.63	0.63	0.60	0.48	.33	.14	.01	.00	3.86
Yr		.05	.18	.36	.56	.70	0.79	0.84	0.84	0.81	0.72	.58	.40	.21	.10	6.34

Table 4b. Monthly-average hourly and daily diffuse irradiation for Cairo

Mo	Days	5–6	6–7	–8	–9	–10	–11	–12	–13	–14	–15	–16	–17	–18	–19	Av day
Jan	372	.00	.00	.14	.36	.54	.65	.71	.71	.65	.54	.38	.16	.01	.00	4.81
Feb	339	.00	.02	.22	.44	.62	.76	.81	.81	.78	.66	.50	.28	.05	.01	5.95
Mar	372	.00	.11	.36	.58	.75	.84	.90	.90	.87	.78	.63	.41	.14	.00	7.26
Apr	360	.04	.29	.55	.76	.89	.96	.99	.98	.93	.83	.69	.49	.23	.01	8.62
May	372	.12	.40	.63	.78	.87	.93	.96	.96	.93	.85	.72	.55	.31	.05	9.03
Jun	349	.14	.41	.60	.71	.75	.76	.77	.77	.72	.69	.64	.51	.35	.09	7.88
Jul	403	.09	.38	.62	.76	.78	.79	.76	.73	.70	.65	.59	.48	.33	.10	7.67
Aug	403	.04	.30	.59	.78	.82	.80	.77	.75	.70	.64	.56	.44	.25	.04	7.39
Sep	390	.01	.22	.49	.69	.78	.76	.74	.72	.68	.62	.52	.35	.12	.00	6.68
Oct	434	.00	.13	.37	.54	.66	.73	.73	.70	.65	.55	.42	.21	.02	.00	5.70
Nov	390	.01	.05	.26	.45	.58	.66	.69	.68	.61	.50	.33	.11	.00	.00	4.88
Dec	403	.01	.01	.16	.36	.50	.59	.63	.64	.57	.46	.30	.10	.02	.00	4.32
Yr		.06	.19	.42	.60	.71	.77	.78	.77	.73	.64	.52	.34	.18	.05	6.65

Table 4c. Monthly-average hourly and daily diffuse irradiation for Aswan

Mo	Days	5–6	6–7	–8	–9	–10	–11	–12	–13	–14	–15	–16	–17	–18	–19	Av day
Jan	311	.00	.03	.24	.39	.50	0.56	0.60	0.60	.56	.50	.39	.22	.03	.00	4.41
Feb	282	.00	.07	.29	.44	.58	0.62	0.67	0.66	.64	.57	.46	.31	.08	.00	5.25
Mar	310	.01	.17	.46	.64	.73	0.80	0.87	0.86	.86	.79	.64	.42	.18	.00	7.27
Apr	300	.05	.34	.59	.75	.86	0.93	0.98	0.98	.95	.86	.73	.55	.24	.01	8.75
May	309	.13	.43	.65	.81	.92	1.00	1.03	1.03	.99	.89	.75	.56	.29	.03	9.41
Jun	300	.15	.39	.54	.63	.70	0.74	0.76	0.76	.74	.70	.62	.51	.33	.06	7.46
Jul	310	.10	.35	.51	.61	.68	0.72	0.75	0.75	.72	.67	.60	.49	.32	.06	7.08
Aug	341	.06	.31	.48	.59	.68	0.74	0.76	0.75	.72	.67	.58	.45	.26	.02	6.24
Sep	296	.03	.27	.48	.59	.68	0.72	0.74	0.73	.72	.64	.53	.37	.12	.00	6.58
Oct	340	.01	.19	.38	.51	.60	0.66	0.69	0.68	.63	.53	.41	.22	.02	.00	5.04
Nov	300	.00	.11	.29	.39	.45	0.48	0.50	0.49	.46	.40	.30	.13	.00	.00	3.93
Dec	341	.00	.05	.23	.35	.42	0.46	0.49	0.48	.45	.39	.28	.13	.00	.00	3.67
Yr		.06	.23	.43	.56	.65	0.70	0.73	0.73	.70	.63	.52	.36	.16	.03	6.23

Table 5a. Monthly-average hourly and daily clearness index values for Matruh

Mo	Days	5–6	6–7	–8	–9	–10	–11	–12	–13	–14	–15	–16	–17	–18	–19	Av day
Jan	309	.000	.000	.346	.400	.480	.532	.543	.552	.540	.516	.451	.356	.000	.000	.491
Feb	282	.000	.000	.383	.456	.534	.573	.602	.600	.591	.560	.524	.452	.355	.000	.527
Mar	278	.000	.469	.433	.532	.602	.637	.656	.666	.653	.630	.584	.517	.378	.000	.606
Apr	297	.000	.415	.530	.616	.672	.698	.714	.715	.704	.686	.629	.559	.455	.517	.597
May	341	.473	.478	.568	.642	.694	.722	.728	.729	.725	.702	.658	.582	.471	.353	.609
Jun	300	.429	.502	.612	.682	.728	.745	.757	.757	.754	.740	.711	.629	.524	.386	.593
Jul	372	.545	.494	.612	.684	.735	.762	.767	.775	.773	.761	.721	.636	.523	.395	.647
Aug	372	.000	.454	.584	.663	.718	.741	.760	.764	.760	.745	.704	.625	.504	.411	.654
Sep	362	.000	.421	.546	.639	.694	.729	.744	.739	.735	.711	.657	.570	.411	.000	.642
Oct	372	.000	.487	.488	.578	.631	.659	.668	.676	.666	.636	.586	.471	.473	.000	.564
Nov	299	.000	.000	.402	.525	.588	.614	.624	.624	.595	.536	.469	.353	.000	.000	.555
Dec	341	.000	.000	.394	.460	.542	.581	.585	.577	.548	.507	.427	.318	.000	.000	.509
Yr		.449	.476	.498	.578	.639	.670	.683	.685	.675	.649	.598	.510	.469	.415	.585

Table 5b. Monthly-average hourly and daily clearness index values for Cairo

Mo	Days	5–6	6–7	–8	–9	–10	–11	–12	–13	–14	–15	–16	–17	–18	–19	Av day
Jan	372	.000	.070	.316	.415	.500	.546	.550	.544	.512	.486	.419	.322	.030	.000	.497
Feb	339	.000	.082	.356	.456	.524	.565	.568	.549	.530	.495	.454	.373	.299	.000	.520
Mar	372	.000	.369	.431	.531	.581	.614	.632	.620	.609	.578	.526	.441	.312	.000	.570
Apr	360	.175	.380	.493	.572	.622	.656	.672	.665	.648	.614	.557	.477	.349	.000	.595
May	372	.326	.435	.539	.611	.657	.677	.684	.679	.664	.636	.588	.508	.389	.301	.598
Jun	360	.329	.455	.568	.643	.690	.714	.725	.721	.711	.682	.637	.565	.447	.308	.619
Jul	403	.306	.401	.521	.610	.670	.702	.717	.721	.711	.684	.639	.568	.445	.299	.614
Aug	403	.274	.357	.484	.578	.652	.686	.703	.705	.694	.664	.612	.525	.386	.203	.609
Sep	390	.000	.339	.476	.566	.633	.669	.683	.681	.667	.625	.561	.449	.305	.000	.596
Oct	372	.000	.345	.458	.544	.601	.629	.642	.638	.615	.567	.485	.350	.085	.000	.558
Nov	390	.000	.301	.379	.472	.544	.576	.580	.565	.537	.501	.411	.285	.028	.000	.519
Dec	403	.000	.065	.329	.424	.497	.540	.560	.547	.525	.484	.400	.285	.028	.000	.493
Yr		.118	.300	.446	.535	.598	.631	.643	.637	.619	.586	.524	.429	.257	.094	.566

Table 5c. Monthly-average hourly and daily clearness index values for Aswan

Mo	Days	5–6	6–7	–8	–9	–10	–11	–12	–13	–14	–15	–16	–17	–18	–19	Av day
Jan	341	.000	.000	.479	.593	.652	.682	.695	.691	.676	.645	.586	.460	.000	.000	.657
Feb	311	.000	.000	.522	.625	.681	.709	.720	.718	.706	.674	.627	.529	.000	.000	.682
Mar	341	.000	.429	.560	.647	.690	.706	.720	.719	.704	.676	.625	.534	.383	.000	.678
Apr	329	.000	.473	.599	.665	.701	.719	.727	.723	.709	.679	.627	.544	.391	.000	.665
May	341	.377	.490	.585	.642	.670	.688	.698	.691	.678	.648	.600	.528	.392	.000	.618
Jun	330	.394	.532	.624	.678	.707	.723	.729	.729	.717	.695	.655	.582	.456	.609	.645
Jul	372	.428	.512	.611	.668	.704	.722	.730	.728	.718	.695	.654	.584	.456	.581	.687
Aug	372	.687	.490	.602	.667	.703	.721	.727	.724	.711	.684	.637	.554	.403	.000	.666
Sep	360	.000	.451	.577	.646	.684	.700	.709	.703	.691	.660	.603	.497	.375	.000	.648
Oct	372	.000	.438	.567	.639	.677	.696	.697	.692	.670	.631	.560	.417	.367	.000	.636
Nov	360	.000	.061	.589	.632	.672	.696	.699	.693	.673	.631	.548	.394	.000	.000	.645
Dec	370	.000	.000	.507	.606	.655	.680	.686	.683	.663	.621	.542	.393	.000	.000	.627
Yr		.447	.489	.566	.643	.683	.703	.711	.708	.693	.661	.604	.500	.423	.593	.648

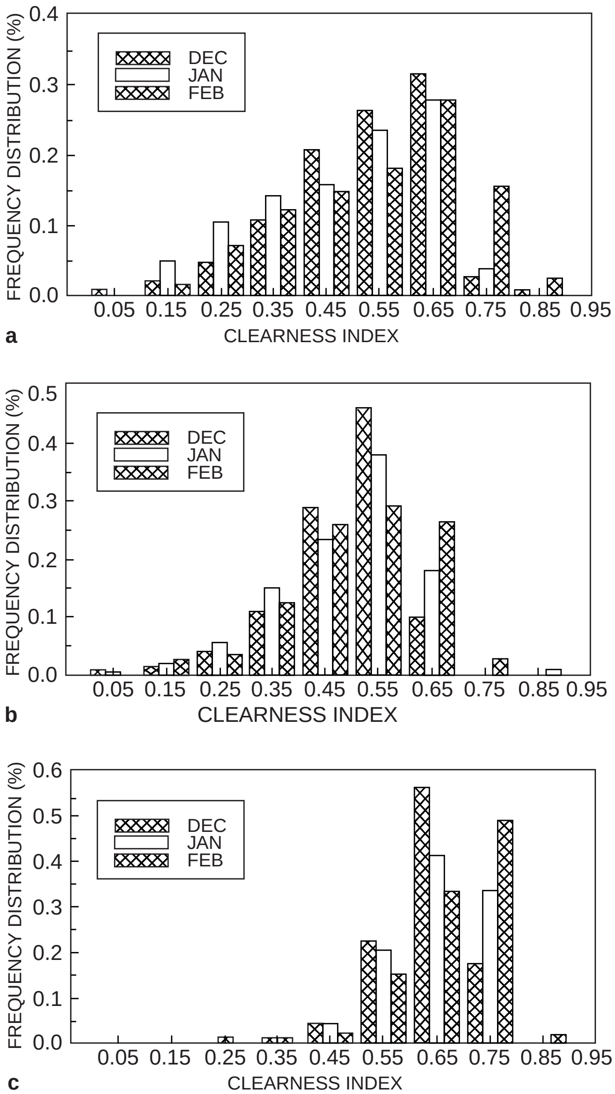

Fig. 2. Monthly percentage frequency distribution of daily clearness index during winter (December, January, February); **a** Matruh, **b** Cairo, **c** Aswan

data, normal-incidence, horizontal global and diffuse, are summarized in Tables 2–4, respectively. Monthly average hourly and daily values are reported for each month together with the number of days per month (listed in parentheses).

The monthly average daily global irradiation on a horizontal surface and its components, the direct and diffuse irradiation, are presented in Fig. 7, together with the sunshine duration, clearness index and diffuse fraction. The tend analysis for these radiational components and ratios is presented in Fig. 8 for the stations Matruh, Cairo and Aswan. The distributions of each of these parameters and ratios for all the Egyptian stations are presented in Fig. 9. The monthly average hourly and daily clearsky index values are listed in Table 5. The daily values were calculated as the ratio of the measured global to extraterrestrial radiation during the time interval between sunrise and sunset, and were averaged to determine monthly average daily clearsky index values. The percentage frequency occurrence for each interval of the clearness index are analyzed on a monthly basis for each season and for the all data in used Figs. 2–6.

5. Discussion

5.1 Statistical analysis of solar irradiation data

WMO (1981) stated that solar radiation data are useful to the solar system designer and developer only if provision is made to reconstruct time series of these data at sufficiently short intervals. Two

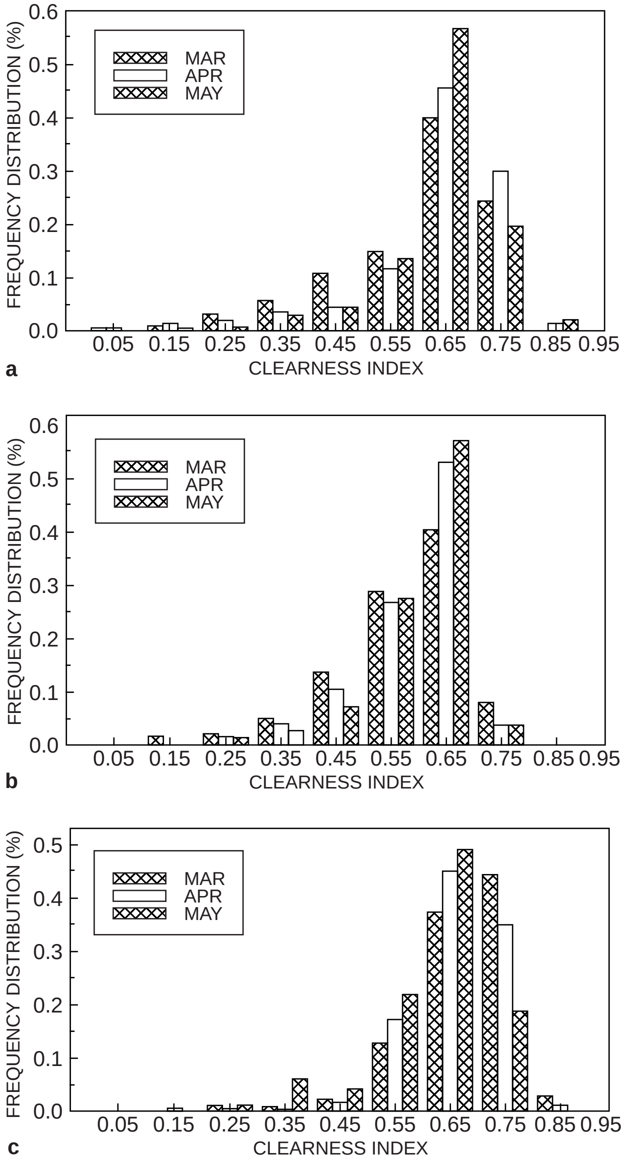

Fig. 3. Monthly percentage frequency distribution of daily clearness index during spring (March, April, May); **a** Matruh, **b** Cairo, **c** Aswan

statistical methods to achieve this were adopted in this analysis.

a) The distribution of large values of both hourly and daily irradiation:

Tables 3a, 3b, 3c show the monthly average hourly and daily global irradiation for the stations Matruh, Cairo, and Aswan. The tables show that large hourly values of global irradiation (2 MJ/m^2) are available in both Matruh and Cairo in February after eleven o'clock and continue to November in Matruh, but to October in Cairo. In Aswan this large value is available throughout the year. This large value reaches a maximum of eight hours per day in both June and July in all the stations. The minimum is zero in both January and December at Matruh and Cairo, but at Aswan it reaches four hours.

b) The persistence of solar irradiation at different time scales:

Autocorrelation is used for measured daily values of global irradiation for each month in the three stations under study. The first three lags (R_1, R_2, R_3) of the autocorrelation are sufficient to describe radiation fluctuations and sequences for all engineering applications. Table 6 presents the first three autocorrelations of the daily global irradiation for the stations Matruh, Cairo, and Aswan for each month. Matruh shows large persistence in the period July to October. In Cairo the data is persisted for larger period (June to October). Aswan shows nearly persistent data all over the year.

Table 6. The first three autocorrelation coefficients of daily values of global irradiation

Month	Matruh			Cairo			Aswan		
Jan	.389	.175	.094	.299	.102	.020	.544	.408	.343
Feb	.277	.069	−.005	.337	.061	.034	.596	.399	.296
Mar	.302	.122	.042	.374	.139	.087	.556	.418	.353
Apr	.328	.012	−.129	.253	.027	.087	.488	.368	.335
May	.266	.025	.076	.254	.179	.016	.686	.498	.345
Jun	.085	.004	.005	.338	.235	.256	.650	.529	.463
Jul	.285	.202	.164	.508	.425	.325	.631	.609	.503
Aug	.790	.655	.594	.639	.533	.446	.631	.542	.542
Sep	.446	.432	.304	.561	.368	.227	.651	.476	.346
Oct	.259	.186	.284	.485	.305	.278	.660	.515	.449
Nov	.337	.094	.171	.379	.205	.107	.562	.435	.312
Dec	.309	.128	.014	.308	.168	.076	.727	.618	.557

5.2 Monthly-average daily solar irradiation

The analysis of the solar irradiation data can be briefly summarized in Table 7.

Table 7. Average daily values and extremes of solar irradiation

Element	Matruh	Cairo	Aswan
Aver. daily I_N	–	16.94	24.46
Max.	–	23.71 Jun	28.34 Jun
Min.	–	11.07 Dec.	22.83 Dec
Aver. daily G	19.40	18.67	21.78
Max.	27.64 Jul	26.83 Jun	27.17 Jun
Min.	.97 Dec	9.97 Dec	14.69 Dec
Aver. daily D	6.34	6.65	6.23
Max.	9.46 Apr	9.03 May	9.41 May
Min.	3.86 Dec	4.32 Dec	3.67 Dec

The above Table 7 shows the following features:

i) Normal incidence radiation at Aswan is higher than that at Cairo. This could be due to its location to the south and the larger amount of turbidity and clouds at Cairo.

ii) Global radiation at Cairo is lower than at Matruh and Aswan inspite of its location between them. This confirms the effect of turbidity at Cairo.

iii) Diffuse radiation at Cairo is higher than that at Matruh and Aswan, which confirms the effect of turbidity at Cairo.

5.3 Hourly distribution of global diffuse and normal incidence radiation

These components have been analyzed to determine the hourly distribution of daily radiation. We divided the day into two parts: the peak insolation hours from 1000 to 1400 and the rest of the day, sunrise to 1000 and 1400 to sunset. December is the month with the maximum and June is the month with the minimum fraction of daily radiation during the peak insolation hours, 1000 to 1400, for the above components. The results are briefly summarized in the following Table 8, which shows the following points:

i) The maximum insolation hours have the smallest percentage of the daily average global and normal incidence beam irradiation at Aswan. This is due to its location at low latitude where the daily range of solar radiation components are relatively small.

ii) The ratio of maximum to minimum for the percentage value of maximum insolation hours to the daily average at Aswan is the smallest among the other stations. This is also due to the effect of the low latitude of this location.

iii) The maximum insolation hours have the largest percentage of daily average diffuse irradiation at Matruh. This is due to its location near the coast, and the relatively permanent cloud occurrence there, particularly cumulus cloud around noon time.

Table 8. Solar irradiation between 10 and 14 hours expressed as percentage of the daily totals

Element	Matruh	Cairo	Aswan
(10–14)/I_N Aver. %	–	61.3	56.3
Max. %	–	75.4 Dec	61.2 Dec
Min. %	–	52.9 Jun	51.5 Jul
F (Max/Min) %	–	1.43	1.19
(10–14)/G Aver. %	67.4	66.4	65.1
Max. %	75.8 Dec	74.9 Dec	72.6 Dec
Min. %	60.1 Jul	59.1 Jun	59.6 Jun
F (Max./Min) %	1.26	1.27	1.22
(10–14)/D Aver. %	63.9	56.9	57.5
Max. %	73.8 Dec	67.8 Dec	63.9 Jan
Min. %	57.6 Apr	47.8 Jun	49.6 Jun
F (Max./Min) %	1.28	1.42	1.29

5.4 Monthly-average daily components of global radiation

Fluctuations in the monthly-average daily values of diffuse radiation are much smaller than those for horizontal global and beam radiation. These fluctuations are presented in the following Table 9, as well as the direct fraction of the monthly-average daily horizontal global radiation.

Table 9. Ratios of extremes of direct, global and diffuse solar irradiation

Element	Matruh	Cairo	Aswan
I_H Aver. (MJ/m^2)	13.61	12.18	15.75
Max. (MJ/m^2)	20.87 Jul	19.20 Jun	19.87 Jun
Min. (MJ/m^2)	6.08 Jan	5.83 Jan	11.52 Jan
F (Max./Min.) I_H	3.43	3.29	1.72
F (Max./Min.) G	2.77	2.69	1.85
F (Max./Min.) D	2.45	2.09	2.56
I_H/G Aver.	67.80	65.20	72.70
Max.	75.50 Jul	71.60 Jun	79.40 Dec
Min.	59.80 Jan	54.80 Jan	63.80 May
F (Max./Min.)	1.26	1.31	1.24

The above table shows the following points:

i) Aswan has the smallest annual range for both horizontal beam and global radiation, due to its location at low latitude.
ii) Cairo has the lowest percentage of beam in the global radiation. This is mainly due to the high levels of air pollution that exist throughout the year, but at the other stations the horizontal beam may decrease during periods of cloudy or sand rising conditions.

5.5 Clearsky index: average values and frequency distribution

The monthly-average hourly and daily values for the clearsky index are listed in Table 4. The monthly-average frequency distributions of the clearsky index are shown in Figs. 2–5. The months have been divided into four groups for the sake of clarity, corresponding to the four seasons experienced in this region, winter–December-February; spring–March-May; summer–June-August; autumn–September-November. The annual-average frequency distribution of the clearsky index is shown in Fig. 6. Throughout the year there is a relatively high frequency of clear days (defined here as $K_T > 0.60$). The results are briefly summarized in the following table:

Table 10. Ratios of global to extra tarrestrial solar irradiation

Element	Matruh	Cairo	Aswan
G/G_0 Aver.	0.583	0.566	0.649
Max.	0.654 Aug	0.619 Jun	0.695 Feb
Min.	0.491 Jan	0.493 Jan	0.627 May
Clear days% Aver.	67.3	43.3	77.6
Max.	88.2	68.8 Jun	83.0 Mar
Min.	31.4 Jan	9.4 Dec	66.7 May

Table 10 shows that Cairo has the lowest values of the clearsky index and in the frequency of clear days. This is due to the high levels of air pollution at this location.

5.6 Annual variation of solar radiation components and parameters

Figure 7a–7f show the annual variation of global, sunshine duration, direct and diffuse irradiation incident on a horizontal surface, and the ratios G/G_0, and D/G for the stations Matruh, Cairo and Aswan. They show a regular annual variation with a maximum in June and a minimum in December for each of the global, direct, diffuse irradiation, and the sunshine duration. The global irradiation component shows the main features of the annual variation at all stations as shown by the direct component and sunshine. Diffuse irradiation has a maximum in both May and April, due to the Khamsin and occurence of sand disturbances. Aswan, a low latitude location, shows a very small annual range. The clearsky index and diffuse fraction analysis show opposite shapes with a kink in May due to the occurrence of sand disturbances.

5.7 Trend analysis of solar radiation components and parameters

Figure 8a–8f show the trend analysis of global, direct, and diffuse irradiation incident on horizontal surface, sunshine duration, and the ratios G/G_0 and D/G for the three stations. These figures and the Table 11 highlight the following points:

i) A generally decreasing trend at all stations for nearly all the components of radiation and ratios except for the diffuse components at Cairo and Aswan, and for the diffuse fraction at all stations. This confirms that in Matruh, diffuse irradiation decreases at a lower rate than global irradiation.

Table 11. Ten years trends of sunshine S, global G, direct I_H and diffuse solar irradiation D

Trend/10 years	Matruh	Cairo	Aswan
S	−0.190	−0.390	−0.080
G	−1.310	−1.390	−1.840
I_H	−0.510	−1.520	−2.080
D	−0.780	+0.060	+0.590
G/G_0	−0.041	−0.045	−0.055
D/G	+0.004	+0.036	+0.047

ii) The increasing trends at Cairo and Aswan may be due to the increase of atmospheric aerosols due to air pollution. The aerosols effect is to decrease direct and global irradiation due to increases in both absorption and scattering. This scattering increases the trend of the diffuse irradiation.

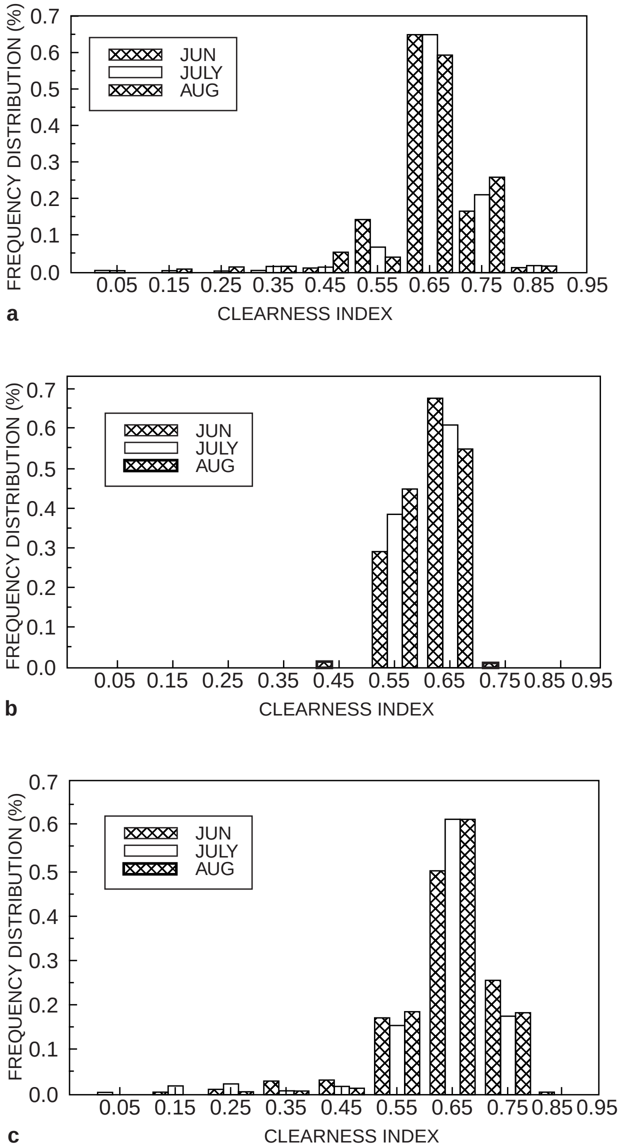

Fig. 4. Monthly percentage frequency distribution of daily clearness index during summer (June, July, August); **a** Matruh, **b** Cairo, **c** Aswan

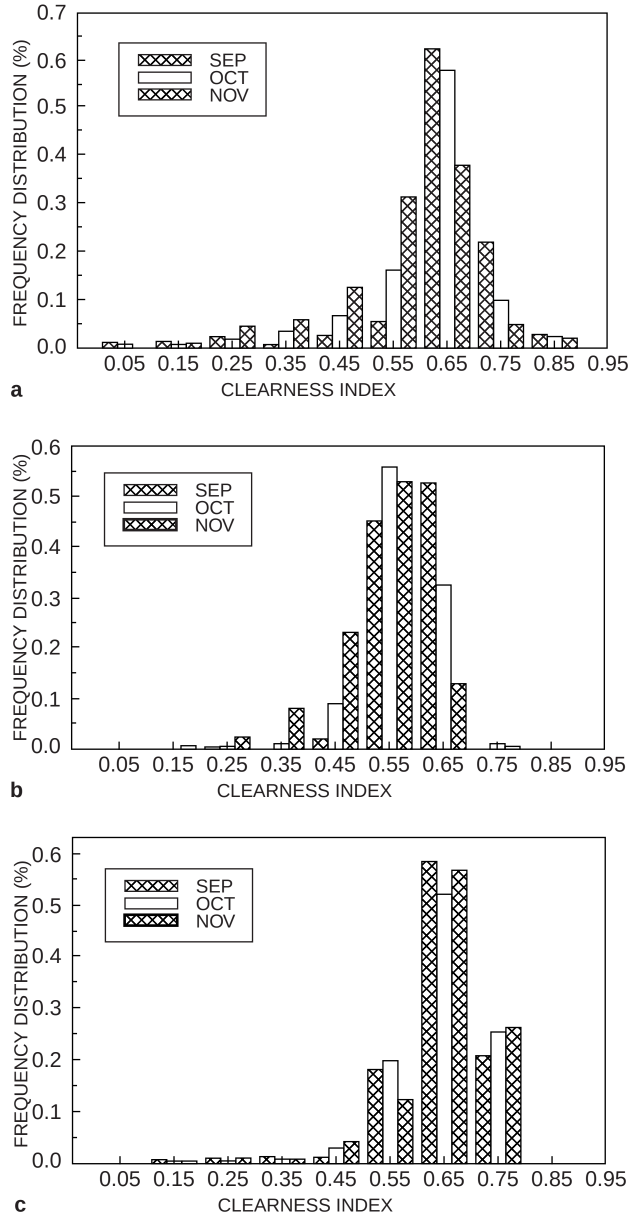

Fig. 5. Monthly percentage frequency distribution of daily clearness index during autumn (September, October, November); **a** Matruh, **b** Cairo, **c** Aswan

iii) The increasing trend in the diffuse fraction at Matruh may be due to the increase in cloud cover and sand storm occurrences which have large effects on the decrease in global radiation.

5.8 Overview of the radiational components and ratios over Egypt

Global and direct irradiation, sunshine duration and the clearsky index show roughly similar distributions with similar features for the five northerly stations at nearly the same latitudes and similar features at the southerly three stations, Asyout, Aswan and Kharga. Diffuse irradiation and the diffuse fraction show nearly opposite distributions, with northerly stations having larger values mainly due to the cloud occurrence and sand disturbances.

Figure 9a–9f show the radiation climate distribution over Egypt. Figure 9a, 9b and 9e show the distribution of global irradiation, sun-

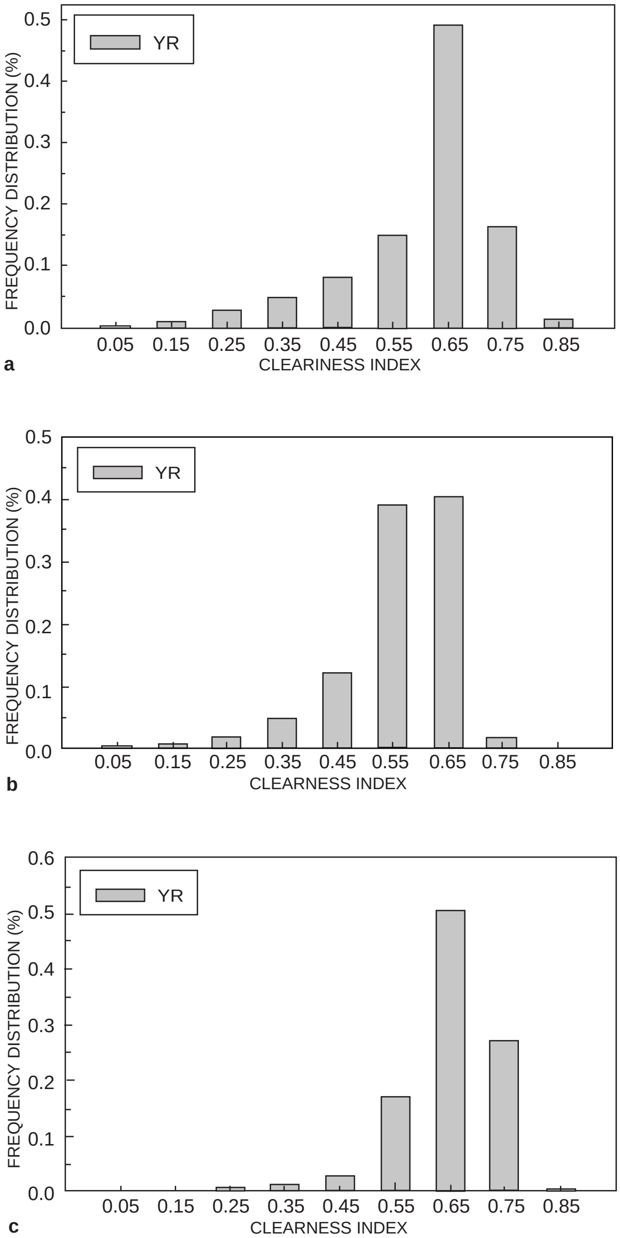

Fig. 6. Annual percentage frequency distribution of daily clearness index; **a** Matruh, **b** Cairo, **c** Aswan

shine duration and clearness index *at eight stations; Matruh, El-Arish, Tahrir, Bahtim, Cairo, Aayout, Aswan, Kharga*. Figure 9c, 9d and 9f show that the distributions of horizontal direct and diffuse irradiation, and the diffuse fraction *at only six stations lie in the same levels as the previous stations without Bahtim and Asyout*.

Global irradiation shows a slight increase with decreasing latitude except at Cairo, where a sudden decrease occurs due to its high pollution characteristics. The large increase continues southward due to the large distances between stations and low level of cloudiness. The average daily global irradiation lies in the range of 19.9 to 23.1 MJ/m^2. This large value of a renewable energy prompts scientists to develop projects to use such energy for developing the country. Sunshine duration shows nearly the same distribution as global irradiation, without the decrease at Cairo. This seems due to the reduced effect of pollution on sunshine duration. The average daily sunshine duration lies in the range of 9 to 10.6 hours. The horizontal direct irradiation shows nearly same distribution and its average daily value lies in the range of 11.8 to 16.2 MJ/m^2. Diffuse irradiation shows large values at northern stations, with a slight decrease southwards, mainly following the distribution of cloud. The average daily diffuse irradiation lies in the range of 6.5 to 7.7 MJ/m^2. The clearsky index shows a similar distribution to that of global irradiation. The average daily clearsky index lies in the range 0.62 to 0.7. The diffuse fraction shows a similar distribution to that of the diffuse irradiation. The average diffuse fraction lies in the range 0.29 to 0.4.

5.9 Comparison of Matruh, Cairo, and Aswan's Solar Radiation Climate with that of Bear Sheva's, in Israel

Table 6 presents a number of parameters characterizing the solar radiation climates at the three Egyptian stations and at Beer Sheva in Israel. The table shows the following points:

i) Beer Sheva has the lowest level of diffuse radiation and relatively high levels of direct beam radiation. This shows that it has a clear atmosphere.
ii) The maximum value of diffuse irradiation at Beer Sheva is two MJ/m^2 lower than at any of the Egyptian stations which confirms the above results.

The above discussion shows that Matruh in Egypt has similar characteristics Beer Sheva in Israel.

6. Conclusions

The solar climate of Matruh, Cairo and Aswan in Egypt have been reported in detail. The analysis

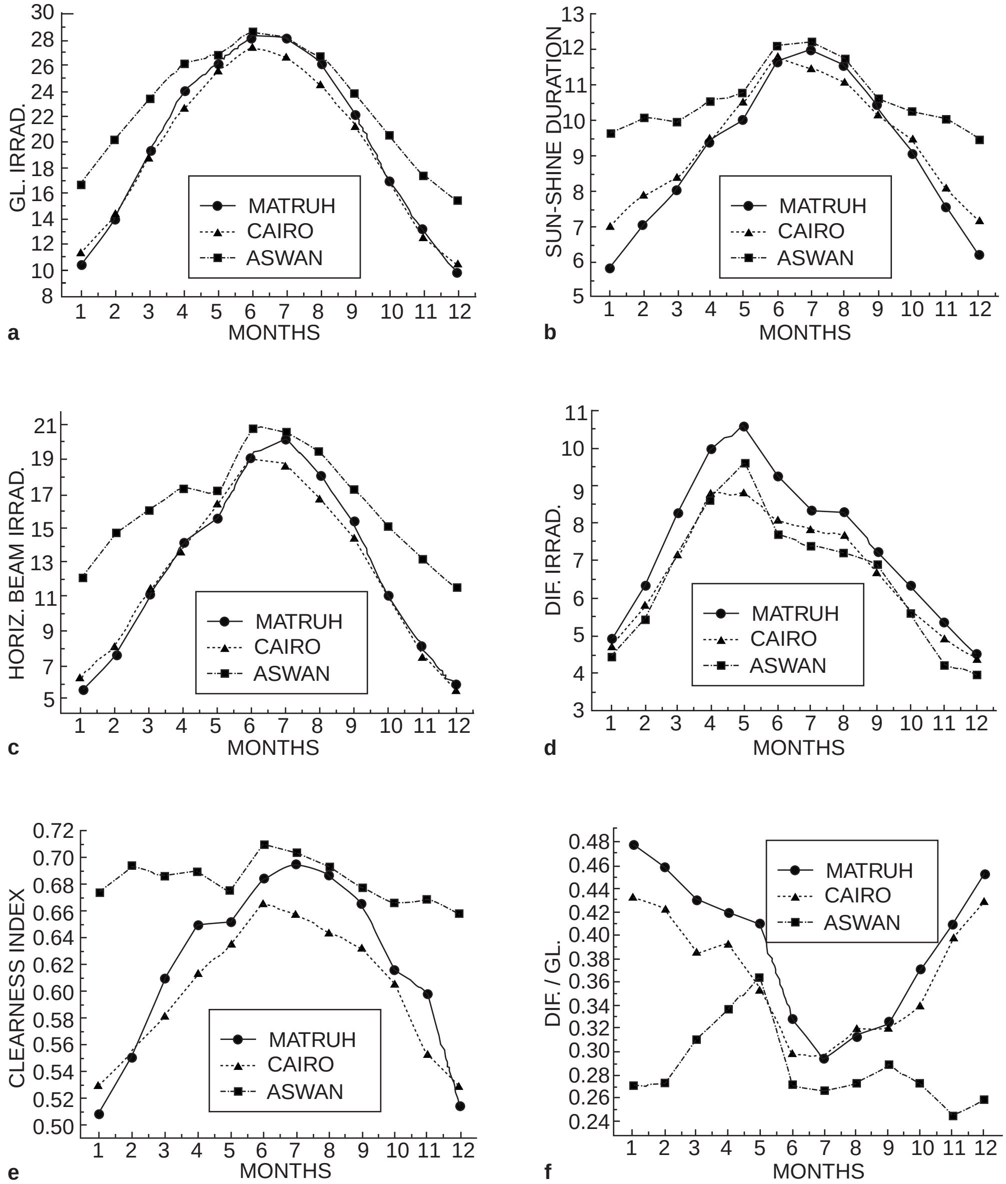

Fig. 7. Monthly average daily solar radiation components and ratioes for Matruh, Cairo, Aswan; **a** sun-shine duration, **b** global irradiation, **c** horizontal beam irradiation, **d** diffuse irradiation **e** clearness index, **f** diffuse fraction

shows the effects of high levels of air pollution in Cairo, the coastal climate at Matruh, and the low latitude climate at Aswan on the solar climate of each of the stations relative to the other two stations. These differences are summarized in the following points:

1. Global radiation at Cairo is in the order of that in the region while the direct radiation, either normal incidence or on horizontal surface is relatively lower, but diffuse radiation is relatively higher than at in the other two stations.
2. The statistical analysis shows that large values of hourly global irradiation (2 MJ m^{-2}) has a maximum of eight hours per day in both June and July, all over the country; but this never occurs at Matruh and Cairo in January and

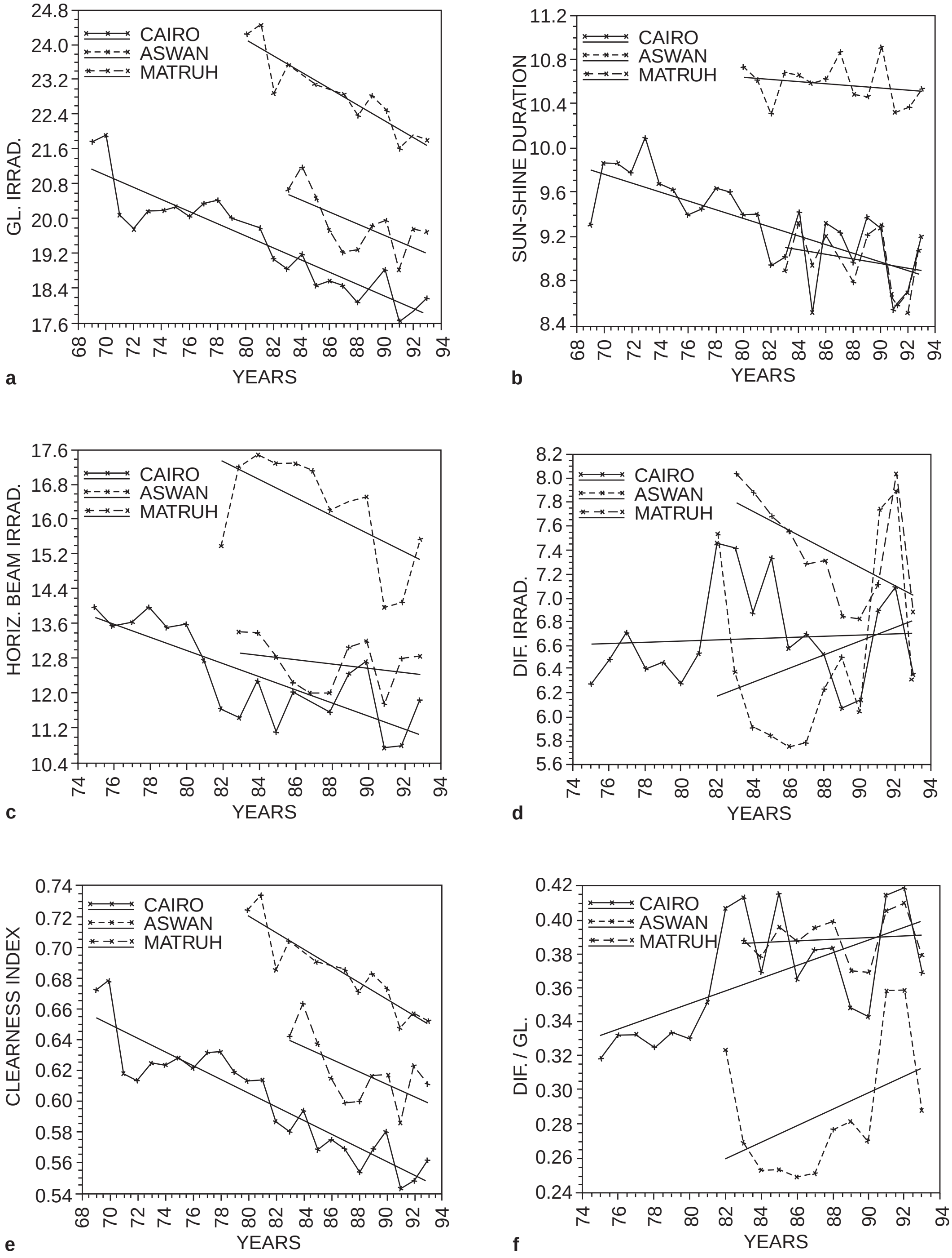

Fig. 8. Trend analysis of yearly average daily solar radiation components and ratioes for Matruh, Cairo, Aswan; **a** sun-shine duration, **b** global irradiation, **c** horizontal beam irradiation, **d** diffuse irradiation **e** clearness index, **f** diffuse fraction

December. It also shows that daily global irradiation is high in Aswan all over the year, while it is high in Matruh and Cairo during the period July to October.

3. The ratio of maximum hourly to total daily irradiance is larger in Cairo because it is a poluted region. This appears in all the components of solar radiation, as they all decrease

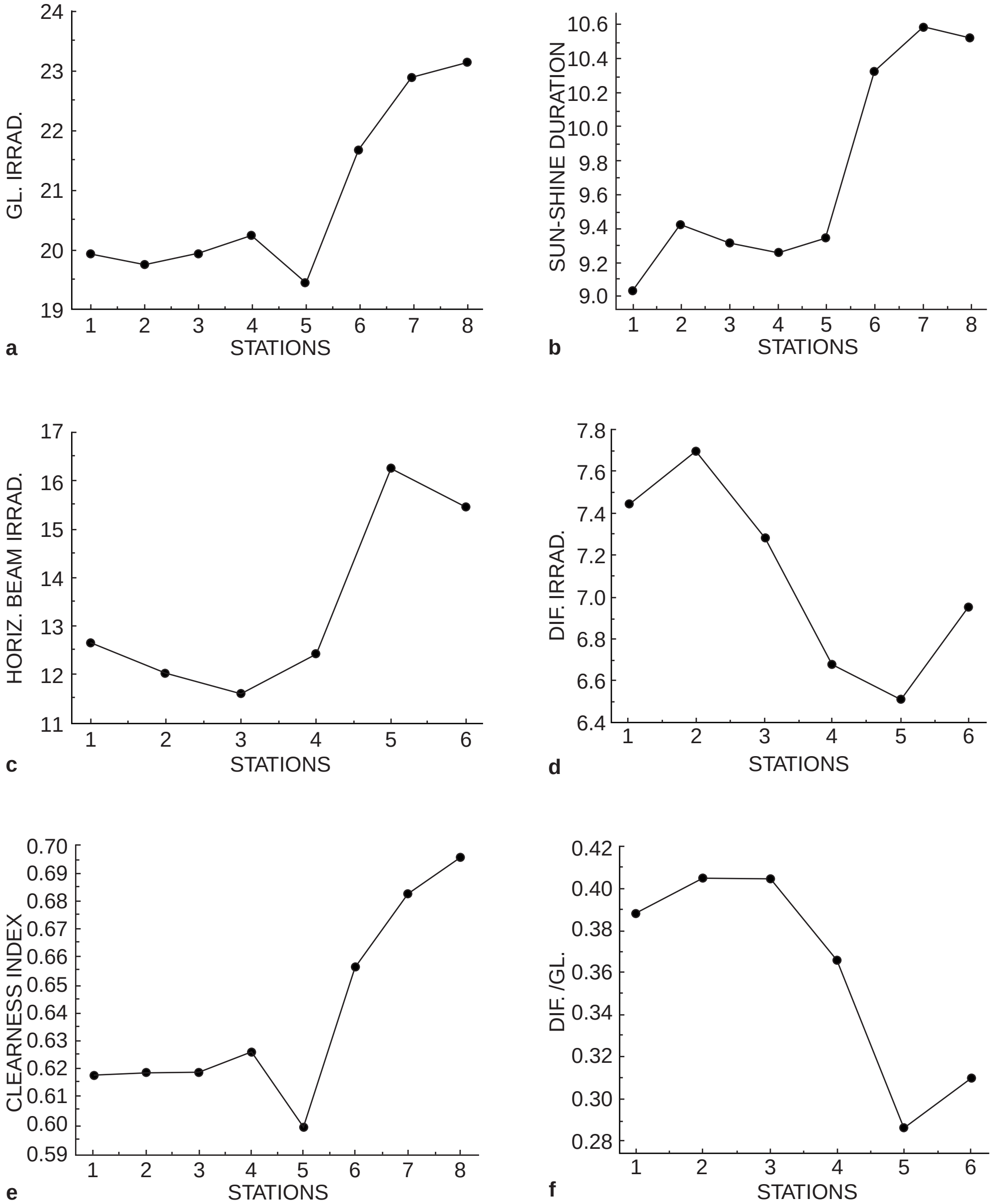

Fig. 9. Distribution of yearly average daily solar radiation components and ratios for the Egyptian net-work stations; **a** sunshine duration, **b** global irradiation, **c** horizontal beam irradiation, **d** diffuse irradiation, **e** clearness index, **f** diffuse fraction. Fig. 9a, 9b and 9e cover eight stations: Matruh, El-Arish, Tahrir, Bahtim, Cairo, Asyout, Aswan, Kharga; Fig. 9c, 9d and 9f cover six stations: Matruh, El-Arish, Tahrir, Cairo, Aswan, Kharga

white large optical airmass, specially in the highly polluted area.

4. The occurrence of clear days (where $G/G_0 > 0.6$) is relatively low.
5. Aswan shows the typical characteristics of low latitude locations of minimum daily and annual range in radiational energy.
6. There is a decreasing trend for all the radiation parameters, except the diffuse radiation and the diffuse fraction (D/G).
7. The distribution of solar climate in Egypt shows characteristics of the solar climate in an urban region of Cairo. It also shows that Egypt has a large amount of this renewable energy.

Table 12. Comparison of Matruh, Cairo, and Aswan's solar radiation climate to Beer Sheva's, Israel

Element	Matruh	Cairo	Aswan	Beer Sheva
Latitude	31° 20′N	30° 05′N	23° 58′N	31° 15′N
Longitude	27° 13′E	31° 17′E	32° 47′E	34° 45′E
Elevation	25.0 m	34.4 m	192.7 m	315.0 m
Annual-average daily solar irradiation MJ/m^2				
Global	19.40	18,67	21.78	18.91
Beam	12.73	12.0	15.47	13.61
Diffuse	6.34	6.65	6.23	5.20
Range of monthly-average daily solar irradiation MJ/m^2				
Global	27.64–9.97	26.83–9.98	27.17–14.69	24.64–9.74
Diffuse	9.46–3.86	9.03–4.32	9.41–3.67	7.46–3.45
Annual and range of monthly average daily ratio of beam to global irradiation				
Annual average	0.65	0.63	0.71	0.72
Maximum	0.76 Jul.	0.72 Jul.	0.76 Aug.	0.82 Jun.
Minimum	0.56 Jan.	0.55 Jan	0.63 Apr.	0.59 Jan.
Range of monthly-average daily clearness index				
Maximum	0.654 Aug.	0.619 Jun.	0.687 Jul.	0.670 Jun.
Minimum	0.491 Jan.	0.493 Dec.	0.627 Dec.	0.495 Jan.
Hourly global radiation at midday				
Maximum	3.62 Jul.	3.41 Jun.	3.49 Jun.	3.43 Jun.
Minimum	1.64 Jan.	1.51 Dec.	2.20 Dec	1.54 Dec.
Average number of hours per day of global irradiation $> 2\,MJ/m^2$	8 Jul.	8 Jun.	8 Jun.	8 Jun.

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