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Yearly, monthly and daily correlations for global solar radiation in Kuwait*

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ABSTRACT

In the present work, yearly, monthly and daily correlations are provided for the maximum, average and minimum global solar radiation in Kuwait. The correlations are based on data pertaining to global solar radiation received by the horizontal plane over the period 1974–1994. The data were fitted by both polynominal and sinusoidal correlations. The conclusions drawn from these correlations are discussed in connection with local weather conditions in Kuwait.

INTRODUCTION

Information on global solar radiation is needed in application fields dealing with solar energy, e.g., sea water desalination by solar energy, solar water heating, solar air conditioning, solar furnaces, photovoltaic applications and medical and agricultural studies (Hovel 1975; Butti & Perlin 1981; Sze 1981; Duffie & Beckman 1991).

The amount of solar radiation incident on a surface of any orientation is usually calculated in terms of solar radiation received by the horizontal plane. This, in turn, is a function of several variables such as the nature and extent of cloud cover, water vapour content, dust and other atmospheric constituents. It is therefore not always possible to predict the actual value of solar radiation for a given location. Nevertheless, the analysis of long term meteorological data on solar radiation makes it possible to predict the most probable expected values of solar radiation at the location of interest (Klein 1977; Katsoulis & Papachristopoulos 1978; Barbaro *et al.* 1978; Villarrubia *et al.* 1980; Leung 1980; Chuah & Lee 1981; Ibrahim 1985; Koronakis 1986; Abdalla 1987; Elhadidy 1991).

Limited information has been published on solar radiation in Kuwait (Quinn *et al.* 1984; Al-Jamal *et al.* 1984; Alaruri *et al.* 1988; Alaruri 1990; Alaruri & Amer 1993). In view of this fact, we considered it appropriate to study this subject. The objective of the present work is to provide correlations of the yearly, monthly and daily global solar radiation incident on the horizontal plane in Kuwait. These correlations are based on the analysis of the data from Kuwait International Airport Observatory (Lat. = 29° 13′ N, Long. = 47° 58′ E, Elev. = 45 m above M.S.L.).

ANALYSIS CONSIDERATIONS

Data on global solar radiation received by the horizontal plane are available from 1974 to the present. It was measured by an Eppley black and white pyranometer (model 8-48) up to the year 1989. The radiation sensor element was a thermopile. Starting from 1992, the global solar radiation was measured by LI-COR INC black and white pyranometer (model LI-200SZ). The radiation sensor element is a high-stability photovoltaic detector. The pyranometer is placed in a horizontal position. It measures the intensity of the global (direct plus diffuse) solar radiation arriving from the upper hemisphere by measuring the total power of the incident solar radiation, and responds, therefore, to the integrated effect of all the wavelengths reaching the ground. Thus, the global radiation measured by the pyranometer is the same type of radiation which is incident upon flat-plate solar collectors, solar plants, or solar cell panels.

Data were received in the form of tables for the years 1974–1989, and on floppy diskettes for the years 1992 to 1994. They were in the form of quarter-hourly data and they were numerically integrated by Simpson's rule to get the daily global solar radiation. Monthly and yearly values were obtained by simple addition.

Data on sunshine duration, obtained from Campbell-Stokes recorders, are available from 1962 to the present. Data in the years 1990 and 1991 are not available due to the Iraqi invasion of Kuwait.

Some applications dealing with solar energy require knowledge of the average values of the global solar radiation at the location of interest, while for other types of applications, the maximum or the minimum values are needed. For this reason the maximum, average, and minimum values over the considered period were studied. These values were computed by 'Excel' software. Special programs were prepared by us for the polynomial and sinusoidal fittings of the data.

RESULTS

Correlations for yearly global solar radiation

The yearly global solar radiation per unit area received by a horizontal plane in Kuwait, $G_y(Y)$ is shown in Fig. 1 for the nineteen years from 1974 to 1994, excluding years 1990 and 1991. The variation of G_y for a certain year Y ($1974 \leq Y \leq 1994$) has been approximated, using the least-squares method, by the following linear relation:

$$G_y(Y) = 8253.134 - 54.7078\ (Y - 1974) \tag{1}$$

where $G_y(Y)$ in correlation (1) is in $MJm^{-2}y^{-1}$. The standard error of estimation of $G_y(Y)$ is 581.8483 $MJm^{-2}y^{-1}$.

Throughout this article the global solar radiation per unit area received by a horizontal plane will be denoted by GSRH. The average value of the yearly GSRH, G_y^{av}, calculated as the arithmetic mean of all values for the years 1974 to 1994, is given by:

$$G_y^{av} = 7740.605\ MJm^{-2}y^{-1}. \tag{2}$$

Correlation (1) and the average value (2) are shown in Fig. 1. The yearly GSRH as estimated by correlation (1) ± one standard error are also shown in Fig. 1. Figure 2 shows the yearly variation of $\{[G_y^{meas}(Y)-G_y^{av}]/G_y^{av}\} \times 100$ which gives the percentage deviation of the measured values, G_y^{meas}, from the average.

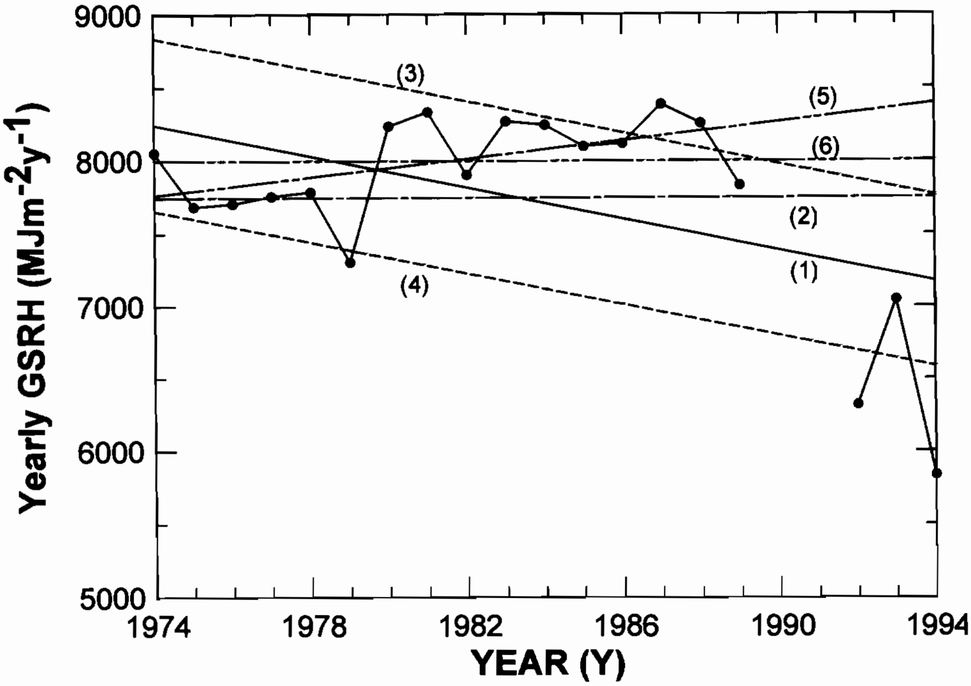

Fig. 1. The yearly GSRH for the years 1974–1994. The dots represent the measured values, curve (1): correlation (1), curve (2): average value (1974–1994), curves (3) and (4): correlation (1) ± one standard error, curve (5): correlation (1a) for the pre-invasion period (1974–1989), and curve (6): the average value (1974–1989).

Correlations for monthly and daily global solar radiation

Figures 3 and 4 show the maximum, average, and minimum values of the monthly and daily GSRH respectively in the period 1974–1994. These values have been least-square fitted by the following fifth degree polynomials:

$$G_m(M) = a_o + a_1M + a_2M^2 + a_3M^3 + a_4M^4 + a_5M^5 \quad (3)$$

and

$$G_d(N) = c_o + c_1N + c_2N^2 + c_3N^3 + c_4N^4 + c_5N^5. \quad (4)$$

In Eq. 3, $G_m(M)$, in MJm^{-2} $month^{-1}$, stands for the monthly maximum, $G_m^{max}(M)$, average, $G_m^{av}(M)$, and minimum, $G_m^{min}(M)$, values of GSRH, for each month M $(1 \leq M \leq 12)$. Similarly, in Eq. 4, $G_d(N)$, in $MJm^{-2}day^{-1}$, stands for the daily maximum, $G_d^{max}(N)$, average, $G_d^{av}(N)$, and minimum, $G_d^{min}(N)$, values of GSRH, for each Julian day N $(1 \leq N \leq 365)$. For values of the polynomial degree $n > 5$, the standard error of estimation of the maximum, average, and minimum monthly and daily GSRH is insignificantly different from its respective values at $n = 5$. Tables 1 and 2 give the polynomial fitting constants for the maximum, average, and minimum values of the monthly and daily GSRH, respectively, together with the corresponding standard error.

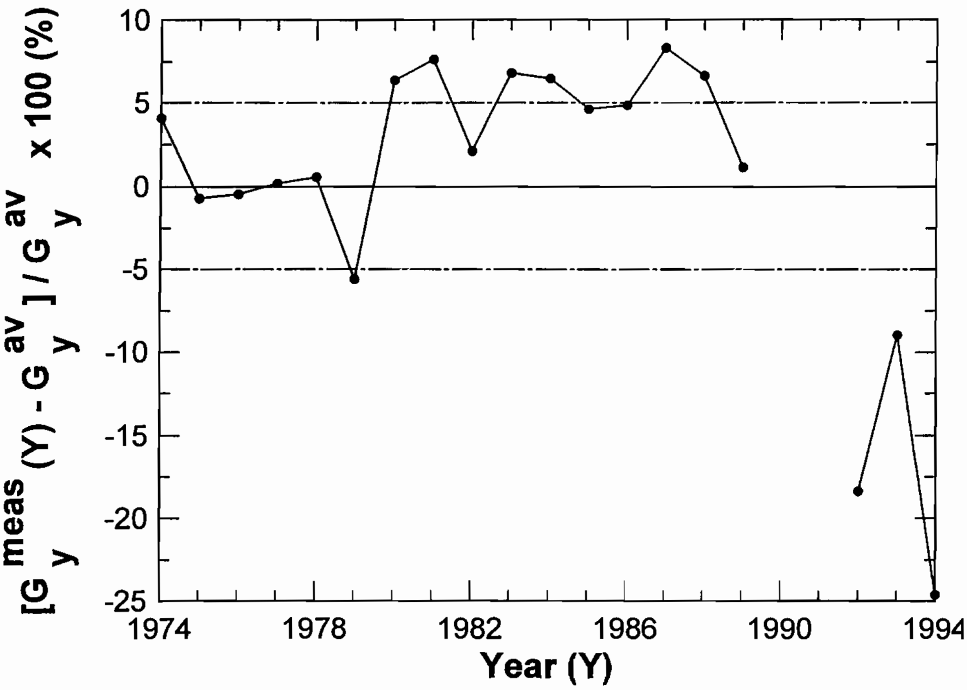

Fig. 2. The yearly variation of $\{[G_y^{meas}(Y) - G_y^{meas}]/G_y^{av}\} \times 100\%$.

Due to their high symmetry, the maximum, average, and minimum values of the monthly and daily GSRH have been also least-square fitted by the following sinusoidal functions:

$$G_m(M) = G_m^0 + A_m \sin(360M/T_m - \theta_m) \tag{5}$$

and

$$G_d(N) = G_d^0 + A_d \sin(360N/T_d - \theta_d) \tag{6}$$

In Eqs. 5 and 6, G_m^o and G_d^o represent the monthly and daily mean value, A_m and A_d the monthly and daily amplitude, T_m and T_d the monthly and daily period, and Θ_m and Θ_d the monthly and daily phase constant, respectively. Tables 3 and 4 give the values

Table 1. The Polynomial Fitting Constants for the Monthly Values of GSRH [Eq. (3)].

Polynomial Constants	Maximum Monthly GSRH $[G_m^{max}(M)]$	Average Monthly GSRH$[G_m^{av}(M)]$	Minimum Monthly GSRH $[G_m^{min}(M)]$
a_0	$+0.4791614 \times 10^3$	$+0.3010250 \times 10^3$	$+0.2116205 \times 10^3$
a_1	-0.3887912×10^2	$+0.1201705 \times 10^3$	$+0.4773901 \times 10^2$
a_2	$+0.5373747 \times 10^2$	-0.2590759×10^2	$+0.1899357 \times 10^2$
a_3	$+0.6165064 \times 10^1$	$+0.9959862 \times 10^1$	-0.3339188×10^1
a_4	$-0.2341230 \times 10^{-1}$	-0.1394968×10^1	$+0.7532038 \times 10^{-1}$
a_5	$+0.1153667 \times 10^{-1}$	$-0.5658343 \times 10^{-1}$	$+0.3856995 \times 10^{-2}$
Standard Error (MJm^{-2} $month^{-1}$)	8.6909	8.1787	14.3059

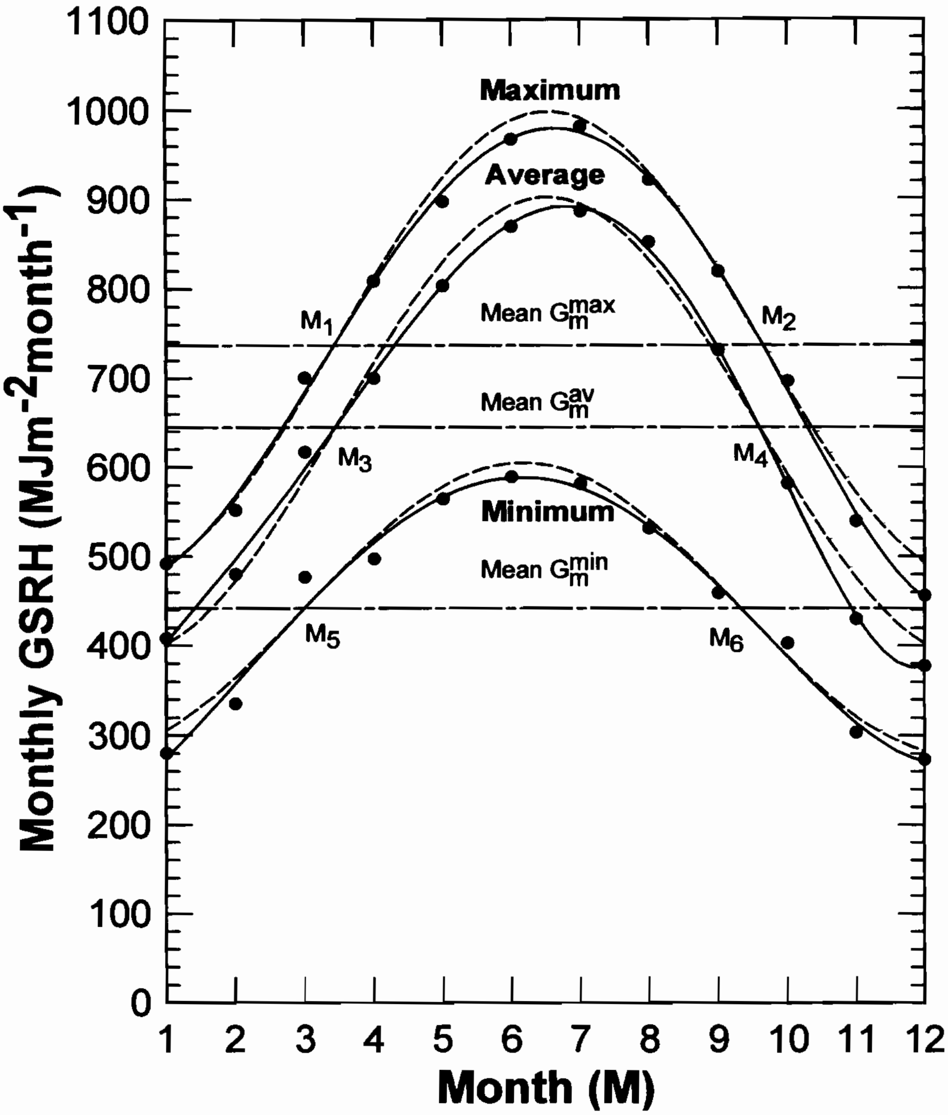

Fig. 3. The annual variation of the maximum, average and minimum values of the monthly GSRH in the period 1974–1994. The dots are the measured values, —— correlation (3) - - - - - correlation (5), and — - — mean values.

of the monthly and daily sinusoidal fitting constants, respectively, together with the corresponding standard error.

In Figs. 3 & 4, the dots (Fig. 3) and the broken lines (Fig. 4) are the measured values, the smooth solid lines are their polynomial fittings, the dashed lines are their sinusoidal fittings, and the dash-dot lines are the mean values.

Figures 5 & 6 show the annual variation of the percentage variability from year to year of the monthly and daily GSRH, respectively, in the considered period, 1974–1994. The percentage variability is defined as [(maximum − minimum)/average] × 100%. The daily variability was fitted by a fifth degree polynomial of the form of Eq. 4.

Table 2. The Polynomial Fitting Constants for the Daily Values of GSRH and Variability [Eq. (4)].

Polynomial Constants	Maximum Daily GSRH [$G_d^{max}(N)$]	Average Daily GSRH [$G_d^{av}(N)$]	Minimum Daily GSRH [$G_d^{min}(N)$]	Daily Variability %
c_0	$+0.1598953 \times 10^{2}$	$+0.1117897 \times 10^{2}$	$+0.1715609 \times 10^{1}$	$+0.1270236 \times 10^{1}$
c_1	$+0.1118564$	$+0.1528044$	$+0.1221500$	$-0.1286778 \times 10^{-1}$
c_2	$+0.6142489 \times 10^{-3}$	$-0.1061917 \times 10^{-2}$	$-0.1044865 \times 10^{-2}$	$+0.1831237 \times 10^{-3}$
c_3	$-0.3627901 \times 10^{-5}$	$+0.1154439 \times 10^{-4}$	$+0.1257761 \times 10^{-4}$	$-0.1399839 \times 10^{-5}$
c_4	$-0.3969080 \times 10^{-8}$	$-0.5417828 \times 10^{-7}$	$-0.5699473 \times 10^{-7}$	$+0.4574770 \times 10^{-8}$
c_5	$+0.1927195 \times 10^{-10}$	$+0.7527401 \times 10^{-10}$	$+0.7663692 \times 10^{-10}$	$-0.5087116 \times 10^{-11}$
Standard Error (MJm^{-2} day^{-1})	1.0632	0.9538	2.8038	17.6788%

The fitting constants and the standard error of estimation of the percentage variability are shown in Table 2.

To be able to interpret the variability of annual monthly GSRH, the percentage sunshine was studied. The percentage sunshine is defined as the ratio of actual duration of sunshine to the length of the day (the possible duration of sunshine) × 100. Sunshine duration values were obtained by Campbell-Stokes recorders (Climatological Summaries, Kuwait International Airport 1962–1982; Monthly Climatological Summaries, Kuwait International Airport 1983–1994). These values were averaged from 1962 to 1994 and are shown in Fig. 7.

Extraterrestrial solar radiation

The daily extraterrestrial radiation on a horizontal surface, H_0, can be calculated using the formula:

$$H_0 = \frac{24 \times 3600}{\pi} G_{sc} \left[1 + 0.033 \cos\left(\frac{360N}{365} \right) \right] \times \left[\cos L \cos\delta \sin\omega_s + \left(\frac{\pi\omega_s}{180} \right) \sin L \sin\delta \right] \quad (7)$$

where G_{sc} is the solar constant, N the Julian day ($1 \le N \le 365$), L the latitude of the locality under consideration, δ the solar declination and ω_s the sunset hour angle in degrees. The value of G_{sc} was taken 1367 W/m^2, as adopted by the World Radiation Center (WRC). For Kuwait International Airport Observatory L = 29° 13′. The solar declination can be calculated from the equation of Cooper (1969):

Table 3. The Sinusoidal Fitting. Constants for the Monthly Values of GSRH [Eq. (5)].

Sinusoidal Constants	Maximum Monthly GSRH [$G_m^{max}(M)$]	Average Monthly GSRH [$G_m^{av}(M)$]	Minimum Monthly GSRH [$G_m^{min}(M)$]
G_m^0–2 $month^{-1}$)	736.3417	645.0504	441.5525
A_m(MJm^{-2} $month^{-1}$)	262.1389	257.3861	163.3479
T_m (month)	12.4679	12.3144	12.6949
Θ_m(degree)	98.6623	100.5277	84.6894
Standard Error (MJm^{-2} $month^{-1}$)	18.8735	22.1328	19.2575

$$\delta = 23.45 \sin\left[360\left(\frac{284+N}{365}\right)\right]. \tag{8}$$

The sunset hour angle is given by

$$\omega_s = \cos^{-1}(-\tan L \tan\delta). \tag{9}$$

Figure 4 shows the daily variation of the extraterrestrial radiation on a horizontal surface, H_0.

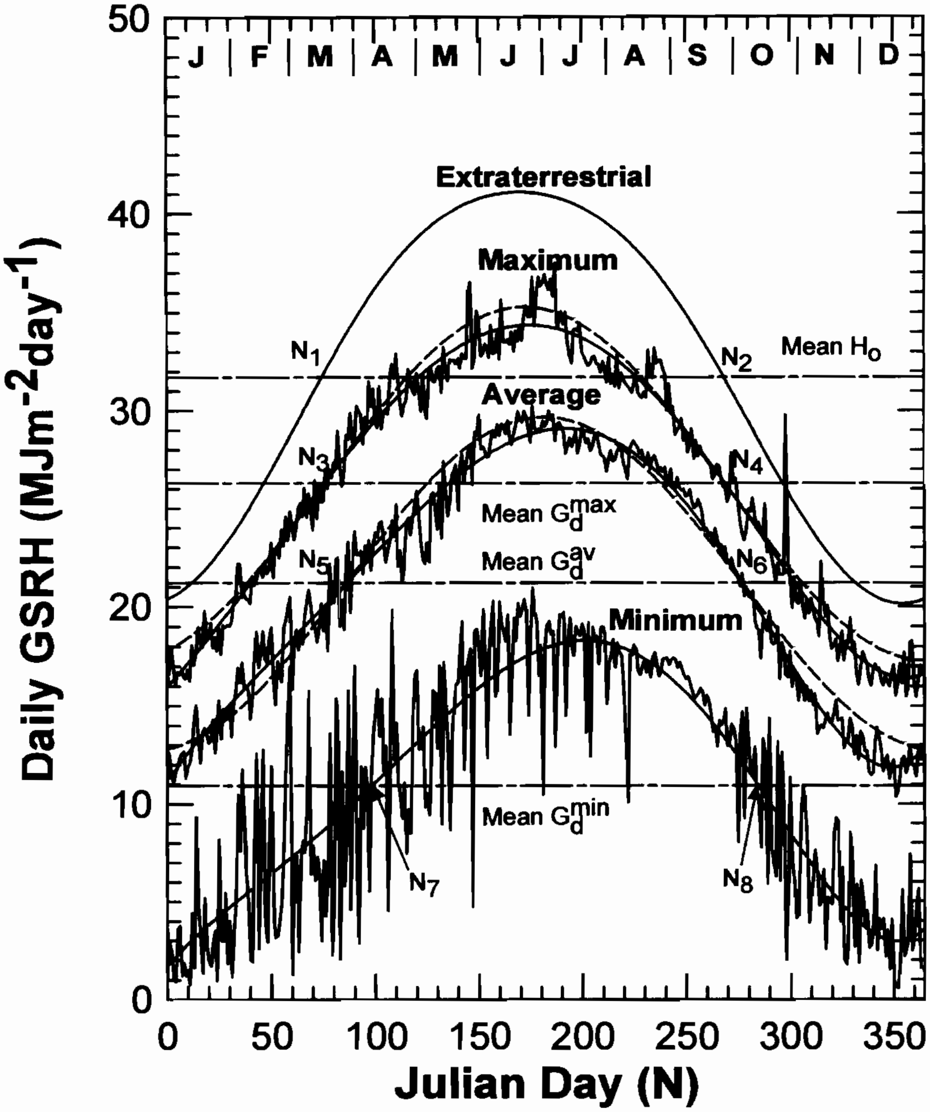

Fig. 4. The annual variation of the maximum, average and minimum daily GSRH in the period 1974–1994, and the annual variation of the daily extraterrestrial radiation on a horizontal surface, according to Eq. (7), and the broken lines are the measured values, —— correlation (4) – – – – correlation (6), and — – — mean values.

Table 4. The Sinusoidal Fitting. Constants for the Maximum and Average Daily GSRH [Eq. (6)].

Sinusoidal Constants	Maximum Daily GSRH [$G_d^{max}(N)$]	Average Daily GSRH [$G_d^{av}(N)$]
G[d10]($MJm^{-2}day^{-1}$)	26.2974	21.2071
A_d($MJm^{-2}day^{-1}$)	8.9864	8.4748
T_d (day)	386.5873	381.5425
Θ_d (degree)	70.3372	81.2088
Standard Error ($MJm^{-2}day^{-1}$)	1.2606	1.2648

DISCUSSION AND CONCLUSIONS

Yearly global solar radiation

From Figs. 1 & 2 the following conclusions may be drawn:

(a) The yearly GSRH in Kuwait in the period 1974–1994 varies between 8385.768 $MJm^{-2}y^{-1}$(1987) and 5834.970 $MJm^{-2}y^{-1}$(1994). The highest value (1987) differs from the average value, relation (2) by 8.33%, while the lowest value (1994) differs from the average by 24.62%.

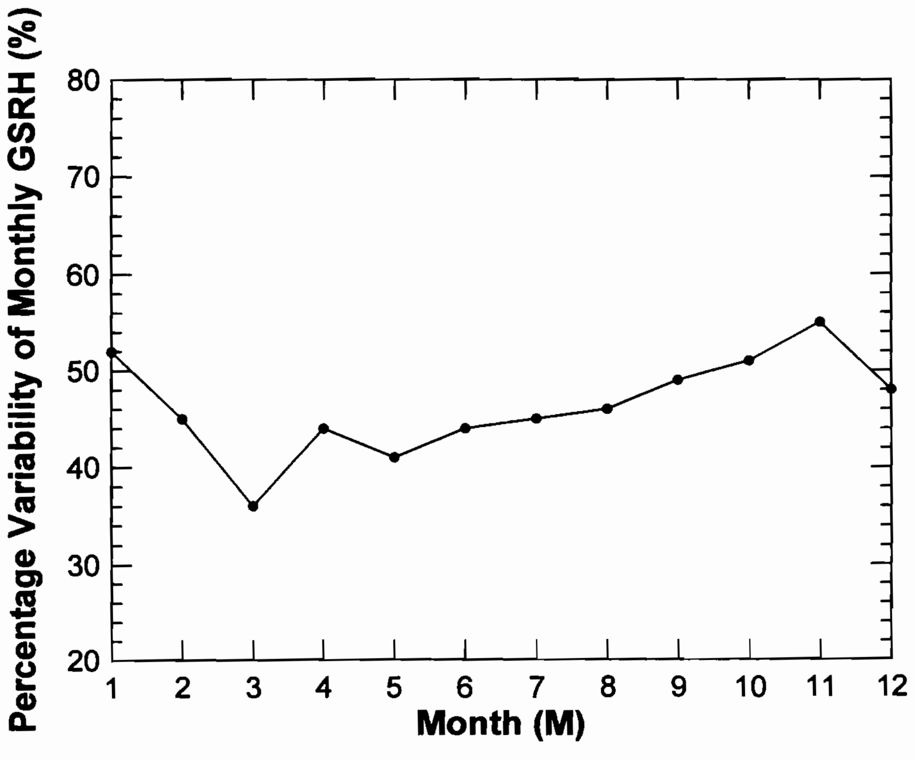

Fig. 5. The annual variation of the percentage variability from year to year of the monthly GSRH in the period 1974–1994. The percentage variability is defined as [(maximum-minimum)/average] × 100%.

(b) The main feature of Eq.1 is the negative slope (– 54.7078 $MJm^{-2}y^{-1}$) which is common to many countries, e.g., in Greece (Katsoulis & Papachristopoulos 1978). The continuous decrease in the yearly global solar radiation can be attributed to the increase of atmospheric pollution.

(c) The yearly GSRH in 1992, 1993 and 1994 differ from the yearly average by – 18.57%, – 8.96% and – 24.62% respectively. It is possible that this significant reduction in solar radiation in the years 1992 to 1994 can be attributed to residual atmospheric pollution as a result of burning oil wells in Kuwait in 1991 (Horgan 1991). If these years were omitted from the analysis, the least-square fitting of Gy for the period 1974–1989, gives

$$G_y(Y) = 7763.679 + 31.3027\,(Y - 1974) \qquad (1a)$$

where Y varies from 1974 to 1989 only, with a standard error of 251.5444 $Mjm^{-2}y^{-1}$. In this case the average value becomes

$$G_y^{av} = 7998.449\ MJm^{-2}y^{-1}. \qquad (2a)$$

On the basis of our present data, it is not possible to conclude the true cause of the reduction in level of the annual GSRH for the years 1992–1994. Careful study of the weather conditions before and after 1990 together with comparing Kuwait data with that of other countries may give a satisfactory explanation. This work will be carried out separately.

(d) Fourteen years out of nineteen (1974 to 1994) differ from the yearly GSRH estimated by correlation (1) by less than ± one standard error.

(e) Nine years out of nineteen (1974 to 1994) differ in their yearly radiation from the average value by less than ± 5% and only two years (1992 & 1994) differ by more than 10%.

Monthly global solar radiation

From Fig. 3, the following conclusions may be drawn:

(a) The 6 summer months, April–September, contribute about 62.6% of the annual total global solar radiation, while the 6 winter months, October–March, contribute 37.4%.

(b) The highest average monthly GSRH occurs in July (886.35 MJm^{-2} $month^{-1}$), contributing about 11.5% of the annual total radiation. On the other hand, December (378.12 MJm^{-2} $month^{-1}$) contributes the least, being responsible for only about 4.9%.

(c) The highest recorded maximum monthly GSRH (981.92 MJm^{-2} $month^{-1}$) was in July 1982. The lowest minimum monthly GSRH (273.69 MJm^{-2} $month^{-1}$) was recorded in December 1992.

(d) The polynomial fitting of the maximum monthly GSRH exhibits a maximum of 979.8459 MJm^{-2} $month^{-1}$ at M = 6.6203. That of the average monthly GSRH exhibits a maximum of 891.9684 MJm^{-2} $month^{-1}$ at M = 6.7977 and a minimum of 375.1194 MJm^{-2} $month^{-1}$ at M = 11.8732. For the minimum monthly GSRH, a maximum of 588.5589 MJm^{-2} $month^{-1}$ is exhibited at M = 6.1514.

(e) The sinusoidal fitting of the maximum monthly GSRH exhibits a maximum of

998.4806 MJm^{-2} $month^{-1}$ at M = 6.5339. That of the average monthly GSRH has a maximum of 902.4365 MJm^{-2} $month^{-1}$, at M = 6.5173. For the minimum monthly GSRH, a maximum of 604.9004 MJm^{-2} $month^{-1}$ is exhibited at M = 6.1600.

(f) The sinusoidal fitting has a period, T_m, of 12.4679, 12.3144, and 12.6946 month rather than 12 month, and a phase constant, Θ_m, of 98.6623°, 100.5277° and 84.6894° rather than 90° for the maximum, average and minimum monthly GSRH, respectively.

(g) The maximum, average, and minimum monthly GSRH have mean values of 736.3417, 645.0504, and 441.5525 MJm^{-2} $month^{-1}$, respectively. The average yearly radiation = 645.0504 × 12 = 7740.605 $MJm^{-2}y^{-1}$, which is the same as that given by relation (2).

(h) The maximum, average, and minimum monthly GSRH are equal to their respective mean values at M_1 = 3.4170 and M_2 = 9.6509 for the maximum, M_3 = 3.4387 and M_4 = 9.5950 for the average, and M_5 = 2.9864 and M_6 = 9.3337 for the minimum GSRH.

From Fig. 5, it can be seen that the monthly percentage variability is high in September (49.17%), October (50.51%), November (54.86%), December (48.28%) and January (51.88%). The percent of possible sunshine in these months is 82.70%, 78.36%, 71.89%, 67.20% and 66.88% as can be seen from Fig. 7. On the other hand, the monthly percentage variability reaches its lowest value in March (36.34%). In Kuwait, in September and October the humidity is high, particularly during the intervals from 15th to 29th September and from 12th to 26th October. During these intervals light easterly and south-easterly winds predominate and because they are coming from the gulf they are burdened with huge amounts of water vapour. Water vapour reduces the amount of solar radiation reaching the earth resulting in large fluctuations in measured maximum and minimum radiation and consequently high variability. In November, December and January, the cold north-westerly current is usually accompanied by thunderstorms resulting in an increase of the cloud sky cover. From 15th March to 10th April, a southerly hot current (locally called 'Suhaili') may prevail and is frequently associated with duststorms. The percent of possible sunshine reaches 62.76%. Irrespective of this low value of percent possible sunshine, March, in Kuwait, is a month of stable weather conditions, and fluctuations in the monthly maximum and minimum radiation is the least over the whole year. This explains the low monthly percentage variability in March.

Daily global solar radiation

From Fig. 4, the following conclusions concerning the daily GSRH may be drawn:

(a) The highest GSRH ever measured in Kuwait in the considered period 1974–1994 was 37.473 MJm^{-2} day^{-1} on July 6, 1984 (N = 187). On the other hand, the least GSRH ever measured in this period was 0.560 MJm^{-2} day^{-1} on December 18, 1982 (N = 352). It is worth mentioning that while the oil wells were burning in Kuwait, the sun was completely screened the whole day, as in nuclear winter, and the least value of GSRH reached true zero (Horgan 1991).

(b) The polynomial fitting of the annual variation of the maximum daily GSRH exhibits a maximum of 34.3734 MJm^{-2} day^{-1} at N = 174.4010, which is about one day later than summer solstice and a minimum of 16.4211 MJm^{-2} day^{-1} at N = 355.7370, which coincides with the winter solstice. That of the average daily GSRH exhibits a maximum of 29.0955 MJm^{-2} day^{-1} at the Julian day N = 191.6930, which is 18 days later than the summer solstice and 8 days later than the aphelion, and a minimum of 11.8768 MJm^{-2} day^{-1} at N = 348.7940, which is about 7 days before the winter solstice and about 18 days before the perihelion. For the minimum daily GSRH, it exhibits a maximum of 18.3060 MJm^{-2} day^{-1} at N = 201.3230 and a minimum of 2.9612 MJm^{-2} day^{-1} at N = 351.7840. The former value of N lies between the summer solstice and autumnal equinox and the latter about 4 days before the winter solstice.

The shift of the maximum of the average daily GSRH from the summer solstice can be attributed to the dry hot north-westerly winds (locally called 'Simoom') prevailing during the 40 day interval from June 6 to July 15. They sometimes raise extensive dust storms which much reduce the received solar radiation, shifting the maximum of the average daily radiation to N = 192 (July 11) close to the end of the summer 40-day Simoom period. On the other hand, humid south-easterly winds prevail during the 40 day interval from December 6 to January 14. The sky is usually cloudy and the winds are sometimes strong enough to raise duststorms. The average received radiation is also reduced during these 40 days and the minimum of the average daily radiation is shifted from the winter solstice.

(c) The sinusoidal fitting of the annual variation of the maximum daily GSRH exhibits a maximum of 35.2838 MJm^{-2} day^{-1} at N = 172.1787, which is about one day before the summer solstice. That of the average daily GSRH exhibits a maximum of

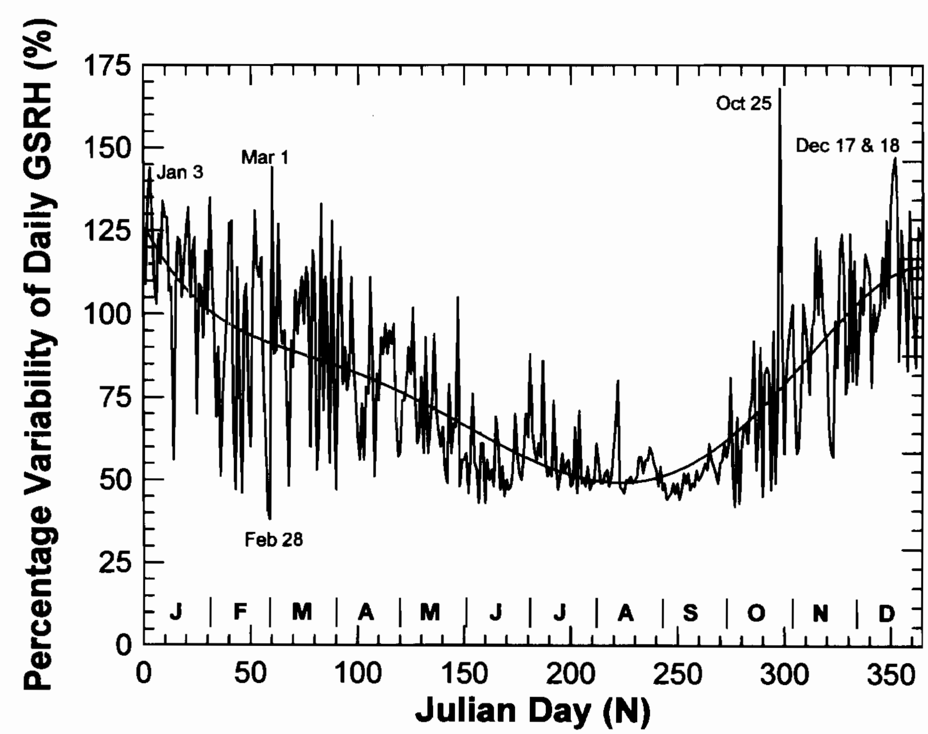

Fig. 6. The annual variation of the variability from year to year of the daily GSRH in the period 1974–1994, defined as [(maximum-minimum)/average] × 100%.

29.6819 MJm^{-2} day^{-1} at the Julian day N = 181.4540, which lies between the summer solstice and the aphelion. The sinusoidal fitting, by its symmetrical nature, tends to have its maximum nearer to the summer solstice than the asymmetrical polynomial fitting.

From (b) and (c) above, it can be seen that the maximum of the maximum daily GSRH is closer to the summer solstice than the maximum of the average daily radiation. This is clear since the maximum radiation is received on clear sky days, where the cloud cover and the duststorms are least, while the average is strongly affected by these factors and its maximum is shifted. For the same reason the maximum daily GSRH exhibits its maximum and minimum values at Julian days, very close to those corresponding to the maximum and minimum extraterrestrial radiation respectively, which is unaffected by the climatological factors.

(d) The sinusoidal fitting has a period, T_d, of 386.5873, and 381.5425 day rather than 365 day and a phase constant, Θ_d, of 70.3372° and 81.2088 rather than 90° for the maximum and minimum daily GSRH, respectively.

(e) The maximum, average, and minimum daily GSRH have mean values of 26.2974, 21.2071, and 10.9412 MJm^{-2} day^{-1}, respectively. The average yearly radiation = 21.2071 × 365 = 7740.592 MJm^{-2} y^{-1}, which is the same as the value given by Eq. 2, and as obtained from the monthly mean value.

(f) The maximum, average, and minimum daily GSRH are equal to their respective mean values at N_3 = 75.5319 and N_4 = 268.8256 for the maximum, N_5 = 86.0684 and N_6 = 276.8397 for the average, and N_7 = 98.1597 and N_8 = 284.7175 for the minimum GSRH. N_3 is about 4 days before the vernal equinox and N_4 is about 3 days later than the autumnal equinox, while N_5 is 6 days later than the vernal equinox and N_6 is about 11 days later than the autumnal equinox.

From Fig. 6, it can be seen that the daily percentage variability reaches values larger than 140% on January 3 (144%); March 1 (144%); October 25 (168%); December 17 and 18 (143% and 147% respectively). It reaches a value lower than 40% on February 28 (38%). The variability is generally high in January, February and March and decreases gradually till it reaches its minimum values in August and September and then increases again gradually to December. The polynomial fitting shows a minimum of 49.1548% at N = 223.0530 (August, 11) and a maximum of 114.1159% at N = 364.1190 (December 30). These results can be interpreted on basis of the percentage of possible sunshine (Fig. 7), where it is least in January, March, April and December and highest in August and September.

Extraterrestrial solar radiation

In the literature, there are many recommended values for the solar constant. Frohlich (1977) recommended a value of 1373 W/m^2 based on data from Nimbus and Mariner satellites. This value has a probable error of 1 to 2%. Additional spacecraft measurements have been made, with Wilson *et al.* (1981) reporting 1368 W/m^2 and Hickey *et al.* (1982) reporting 1373 W/m^2. Measurements from three rocket flights reported by Duncan *et al.* (1982) were 1367, 1372 and 1374 W/m^2. In Eq. 5, the value of the solar constant G_{SC} = 1367 W/m^2 was used. This value, which was adopted by the World Radiation Center (WRC), has an uncertainty of the order of 1% (Iqbal 1983). As a

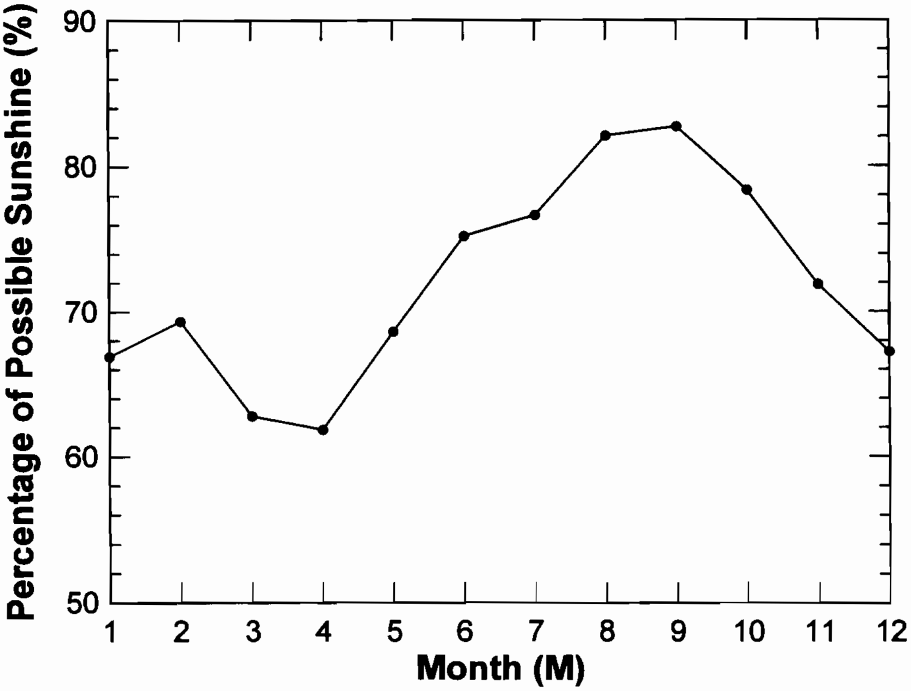

Fig. 7. The monthly variation of percentage sunshine defined as the ratio of the actual duration of sunshine to the length of the day (the possible duration of sunshine) × 100. The values shown in the figure are averaged from 1962 to 1994.

matter of fact, uncertainties in most terrestrial solar radiation measurements are of an order of magnitude larger than those in G_{SC} (Duffie & Beckman 1991).

In Eq. 7, the term [1 + 0.033 cos(360N/365)] takes account of the daily variation in the earth-sun distance.

From Fig. 4, it can be seen that the extraterrestrial solar radiation on a horizontal surface has a daily average value of 31.7060 MJm^{-2} day^{-1} and exhibits a maximum of 41.0892 MJm^{-2} day^{-1} at the Julian day 169.750 and a minimum of 20.1553 MJm^{-2} day^{-1} at the Julian day 354.370. The maximum occurs 3 days before the summer solstice (June 22; N = 173) and 13 days before the aphelion (July 2; N = 183). The minimum occurs two days before the winter solstice (December 22; N = 356) and 11 days before the perihelion (January 2; N = 2). The extraterrestrial solar radiation has a value equal to its average at $N_1 = 74.2257$ and $N_2 = 268.4135$. N_1 is 6 days before the vernal equinox (March 21; N = 80) and N_2 is 2 days later than the autumnal equinox (September 23; N = 266).

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العلاقات السنوية والشهرية واليومية للإشعاع الشمسي الكلي بدولة الكويت

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خلاصة

تزودنا هذه الدراسة بالعلاقات السنوية والشهرية واليومية للقيم العظمى والمتوسطة والصغرى للإشعاع الشمسي الكلي بدولة الكويت.

وقد بنيت هذه العلاقات على بيانات الإشعاع الشمسي الكلي على المستوى الأفقي في الفترة من 1974 الى 1994 وقد تم تزويد هذه البيانات بعلاقات متعددة الحدود وعلاقات جيبية كما تمت مناقشة هذه العلاقات وارتباطها بالظروف المناخية المحلية لدولة الكويت.