Solar Irradiation Isolines for Rapid Design of Solar Systems in Nigeria

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ABSTRACT

Solar irradiation isolines for the twelve months of the year have been developed for Nigeria using various estimates and available data. Among the methods used are linear and quadratic correlations of irradiation with relative sunshine duration, the correlation of cloud amount with relative sunshine duration and with irradiation, and the correlation of irradiation with climatological factors such as relative humidity, temperature, sunshine hours, latitude and altitude.

INTRODUCTION

In order to apply solar energy at any site, it is necessary to have reliable information about the available solar irradiation (insolation). Normally this information is obtained from an analysis of accumulated data on solar radiation, measured as near as possible to the site, usually from existing meteorological stations.

However, at many of these stations, especially in a developing country such as Nigeria, there are very few accurate and uninterrupted measurements of solar irradiation extending over even a few years available. Furthermore, since solar irradiation mapping is not usually a determining criterion in the establishment of these stations, areas of highest irradiation may not necessarily have solar radiation measuring instruments installed there. In addition, solar radiation measurements require relatively expensive and sophisticated equipment which may not be obtainable and the required expertise may be lacking for many local stations in developing countries.

Such a state of affairs has led some previous investigators [1–9] to estimate global irradiation from other more readily available climatological data such as sunshine hours, rainfall, air temperature and relative humidity. In many developing countries reliable data on these other climatological factors have existed for many years. These parameters have been correlated to global solar irradiation using a number of empirical methods, some of which have been used to produce the irradiation charts in this work. The methods chosen produce estimates within 10% of the measured insolation data in Nigeria [11,12]. Figure 1 shows the locations of sixteen stations which have reliable data on relative humidity, sunshine hours, cloud amount, and temperature which are required in some of the methods considered here. A few of the stations have global solar irradiation data for a varying number of years.

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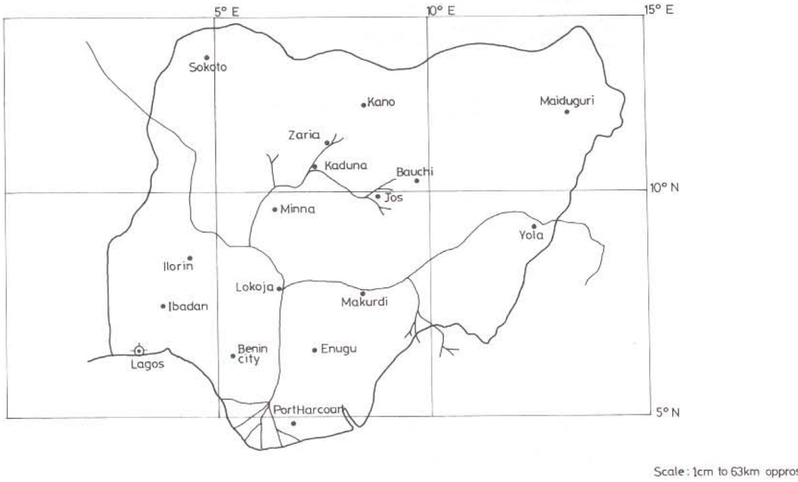

Fig. 1. Location of the stations considered in this study.

CONSIDERATION OF SOME OF THE EMPIRICAL FORMULATIONS EMPLOYED

Method of Angstrom

Perhaps the simplest and most successful radiation correlation is the Angstrom-type equation, subsequently modified by Page [13], relating global solar irradiation directly to relative sunshine, viz:

$$H = H_o(\mathrm{a} + \mathrm{b}S) \tag{1}$$

where H, H_o are the horizontal global and extraterrestrial radiation respectively at the location of interest; **a** and **b** are climatologically determined regression constants dependent on location; and S is the relative sunshine or per cent possible sunshine hours, defined as the ratio of the actual hours of bright sunshine to the day length hours from sunrise to sunset.

With the values of H, H_o and S available at any location, the regression constants **a** and **b** can be readily evaluated. However, as already noted, reliable and sufficient data on the global insolation H are difficult to come by in many meteorological stations. Frere et al. [7] therefore proposed a graphical relationship between the constants **a** and **b** and the annual average values of the relative sunshine duration for several stations with latitudes ranging from 35°S to 50°N. The graph is reproduced in Fig. 2. This method of determining the regression constants may be preferable to the method used by Page [3] and by Lof et al. [9] of using vegetation and climate to fix values for whole regions and sites when vegetation changes are not accompanied by marked changes in climatic conditions.

Table 1 shows the geographical data and climatic constants **a** and **b** for the sixteen stations considered in this study. The annual average relative sunshine is obtained from Ref. [13].

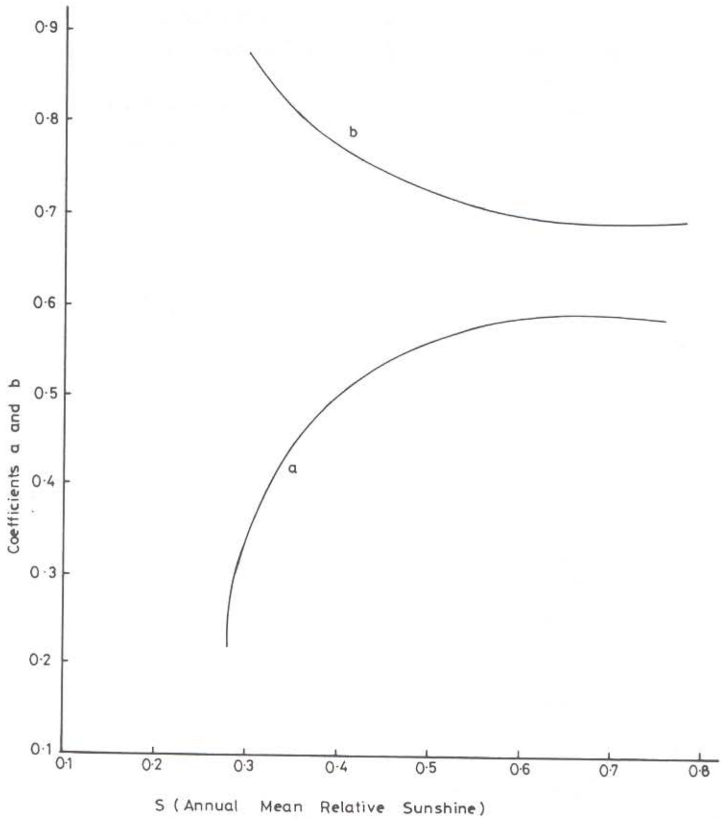

Fig. 2. Relationship between the coefficients **a**, **b** and the annual average relative sunshine S (after Frere et al. [7]).

However, when the regression constants **a** and **b** were determined from a regression analysis of the available data, the following equations were obtained:

$$H/H_o = 0.048 + 0.804\,S \qquad (2)$$

applicable for Northern Nigeria and $r = 0.80$;

$$H/H_o = 0.307 + 0.321\,S \qquad (3)$$

applicable for Southern Nigeria and with $r = 0.82$;

$$H/H_o = 0.353 + 0.254\,S \qquad (4)$$

applicable in the months of November through February in Southern Nigeria when the harmattan dust storms from the north-east trade winds are at their peak; and

$$H/H_o = 0.301 + 0.358\,S \qquad (5)$$

applicable for the rainy season months of May to October in Southern Nigeria.

Table 1. Geographical data and climatic constants a and b for the 16 stations considered in this study (see equation 1).

Station and State	Longitude (°N)	Latitude (°E)	Altitude (m)	Annual Mean Relative Sunshine	Climatic Constants (Frere Values)	
					a	b
1. Port Harcourt, RVS	4.86	7.02	15	35	0.19	0.56
2. Benin City, BDS	6.32	5.62	79	43	0.25	0.47
3. Lagos, LGS	6.45	3.40	3	43	0.25	0.47
4. Enugu, ANS	6.47	7.55	140	48	0.27	0.44
5. Ibadan, OYS	7.43	3.90	198	45	0.26	0.46
6. Makurdi, BNS	7.70	8.58	111	54	0.30	0.43
7. Ilorin, KWS	8.43	4.50	366	53	0.29	0.43
8. Lokoja, KWS	8.80	6.73	98	55	0.29	0.43
9. Yola, GGS	9.22	12.48	215	68	0.32	0.40
10. Minna, NGS	9.62	6.53	323	61	0.31	0.41
11. Jos, PLS	9.87	8.90	1260	63	0.31	0.41
12. Bauchi, BAS	10.33	9.83	620	68	0.32	0.40
13. Kaduna, KDS	10.58	7.43	644	63	0.31	0.41
14. Maiduguri, BOS	11.85	13.08	354	72	0.31	0.41
15. Kano, KNS	12.05	8.53	470	71	0.31	0.41
16. Sokoto, SOS	13.02	5.25	351	73	0.31	0.41

Quadratic Correlations

When the simple quadratic correlation is employed to the available data, the following regression constants are found for data from Southern Nigeria:

$$H/H_o = 0.281 + 0.490\,S - 0.188\,S^2 \tag{6}$$

with $r = 0.76$;

$$H/H_o = 0.000354 + 1.295\,S - 0.768\,S^2 \tag{7}$$

with $r = 0.87$ and applicable for the harmattan season months of November to February;

$$H/H_o = 0.0191 + 1.819\,S - 1.729\,S^2 \tag{8}$$

with $r = 0.90$ and applicable for the rainy season months of May to October.

Maximum-likelihood Quadratic Fit

A maximum-likelihood quadratic fit to the available data produced the following equations:

$$H / H_o = 0.376 - 0.138\, S + 0.66\, S^2 \tag{9}$$

for data from all over the country;

$$H / H_o = 0.301 - 0.30\, S + 0.098\, S^2 \tag{10}$$

applicable for Southern Nigeria;

$$H / H_o = -0.12 + 1.32\, S - 0.388\, S^2 \tag{11}$$

applicable for Northern Nigeria.

These equations estimate solar radiation well within 10 per cent of data from the various stations considered.

Cloud Data Correlation

Some stations were found to have longer and more consistent cloud amount data than radiation data. Thus, correlation equations were developed relating possible sunshine to cloud amount C. Thus, using any of the foregoing equations, it is possible to estimate radiation from cloud amount data [14]:

$$(1 - S) = 0.344\, C - 0.0925\, C^2 + 0.00827\, C^3 \tag{12}$$

applicable for southern Nigeria with latitude < 9°N

$$(1 - S) = 0.222\, C - 0.0649\, C^2 + 0.00634\, C^3 \tag{13}$$

applicable for northern Nigeria with latitude > 9°N.

Method of Sabbagh, Sayigh and El-Salaam

Sabbagh, Sayigh and El-Salaam [6] proposed the following equation for the estimation of global radiation in arid and semi-arid climates:

$$Q = \alpha K \exp L [D - R^{\frac{1}{3}} / 100 - 1 / t] \tag{14}$$

where Q is the monthly mean daily total solar radiation in MJ/(m^2-day), L is the location latitude in radians, D is the hours of bright sunshine relative to 12 hr, R is the relative humidity, t is the maximum air temperature, K is a factor equal to $(\lambda N + w_{i,j} \cos L)\, 10^2$ where λ is a latitude factor equal to $0.2 / (1 + 0.1\, \phi)$, $w_{i,j}$ being the Reddy seasonal factor, N is the mean length of the day during the month, ϕ is the location latitude in degrees and α is a coefficient set equal to 1.53 for the desert climate investigated by Sabbagh et al. when Q is in g-cal/(cm^2-day).

It has been found that, in order for this method to satisfactorily predict insolation in the temperature climatic areas of Italy, the following modification is necessary:

$$\alpha = 1.15 (1 + 0.4 \cos (j + 6) \pi / 6) \tag{15}$$

Barra [10] found that defining α as in equation (15) above yields predictions within 10% of the data all over Italy except at sites high on the mountains where the temperature is near or below 0°C. Similarly, the present author [11] has found that the following modification is necessary for the Sabbagh formula to be applicable to the tropical climate of Nigeria:

$$\alpha \equiv \alpha_j = A(1 - 0.1 \sin(j + 5)p/5) \quad (16)$$

where

$$A = 1.34(1.05(1 - \delta_1) + 0.90(1 - \delta_2) + \delta_3) \quad (17)$$

and δ_1, δ_2, δ_3 are either 0 or 1 depending on the month of the year or the season of the year.

All the above correlations have been used to predict the insolation throughout Nigeria well within 10% of the available radiation data [11,12,14].

DISCUSSION OF RESULTS

Radiation isolines for Nigeria based on the above correlations and estimates are presented in Figs. 3 to 11 for the twelve months of the year. It is noteworthy that, for any month of the year, total solar radiation in Nigeria increases with latitude from the south to the north. Furthermore, there is a noticeable difference in the solar radiation between the southern and the northern sites. This difference ranges between 5 MJ/(m^2-day) and 10 MJ/(m^2-day) for all the months of the year.

Generally, the influence of the rainy season in May to September is most marked in the southern areas when the global solar radiation attains significantly lower values than for the other months of the year.

The lowest values of global solar radiation throughout the year are attained in the month of August (Fig. 8). With the amount of solar radiation shown in these figures, it is apparent that solar energy devices can be usefully employed in Nigeria, even in the southern areas which show monthly averages of not less than 12 MJ/(m^2-day). From the annual average relative sunshine data in Table 1, however, it is seen that most of this radiation is diffuse at latitudes less than 9°N. On the other hand, global solar radiation in excess of 20 MJ/(m^2-day) is generally available in the northern areas of the country, much of which is also diffuse due to the harmattan dust storms from north-east trade winds of October to March or April.

CONCLUSION

The global total solar radiation ranges from a low of about 12 MJ/(m^2-day) in the southern areas to as high as 24 MJ/(m^2-day) in the northern-most areas dependent on the season. There is a conspicuous absence of meteorological stations in the north-western part of the country in this study. It is imperative that many more meteorological and climatological stations all over the country be established in order to improve on the perceived radiation isolines presented in this paper.

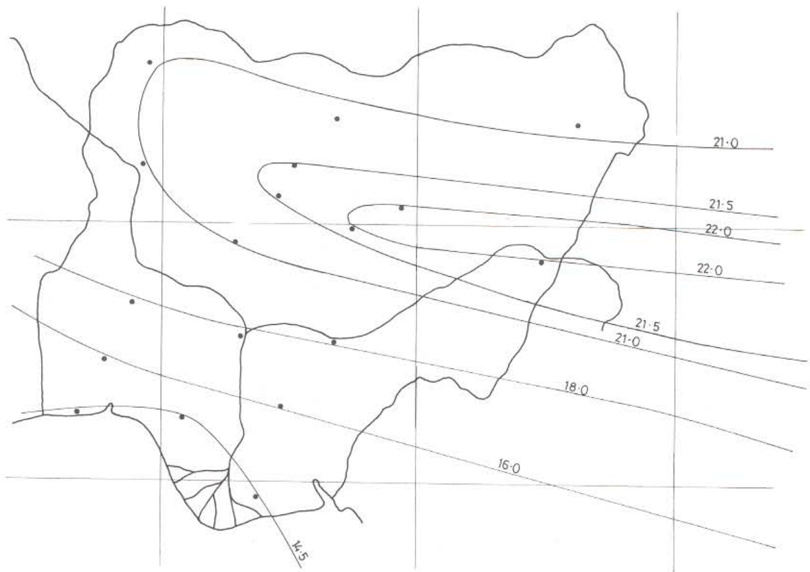

Fig. 3. Radiation isolines for Nigeria in the months of January and December (MJ/m²-day).

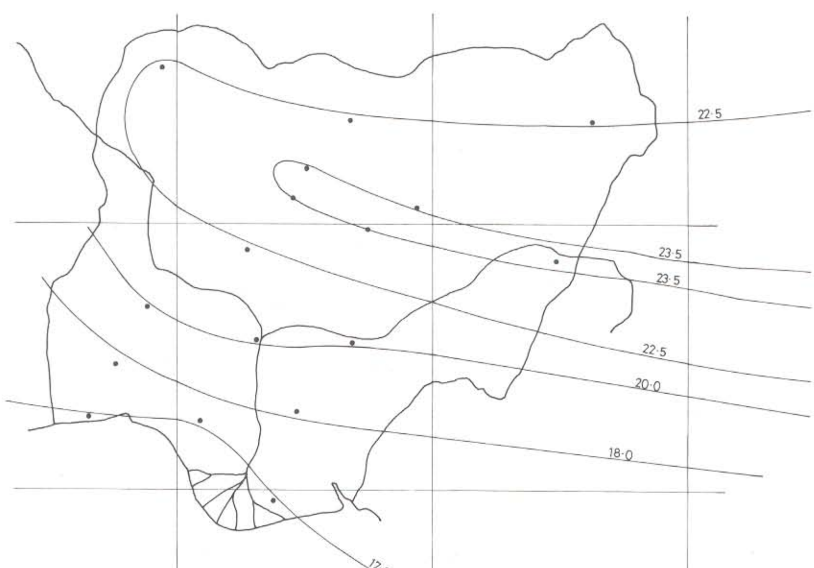

Fig. 4. Radiation isolines for Nigeria in the months of February, March and April (MJ/m²-day).

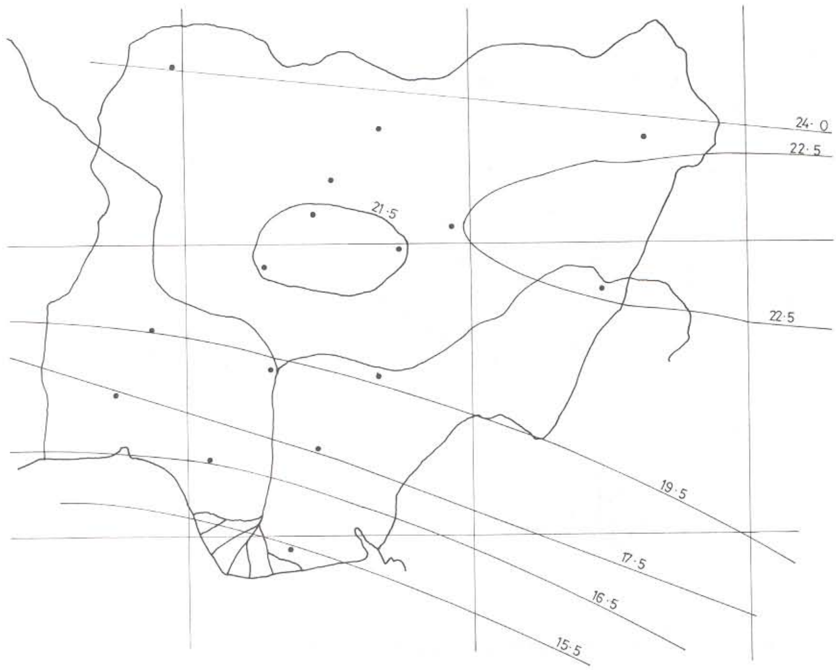

Fig. 5. Radiation isolines for Nigeria in the month of May (MJ/m²-day).

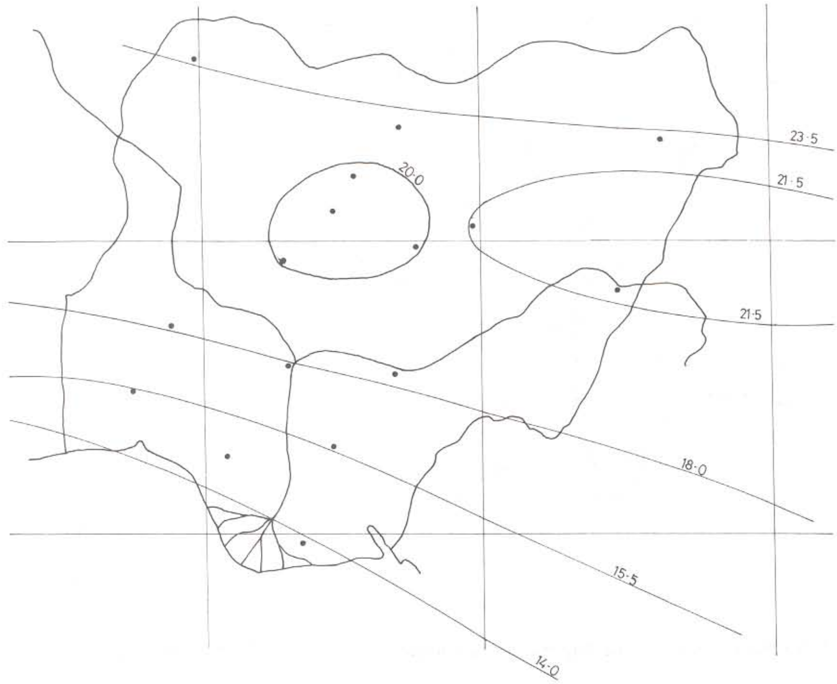

Fig. 6. Radiation isolines for Nigeria in the month of June (MJ/m²-day).

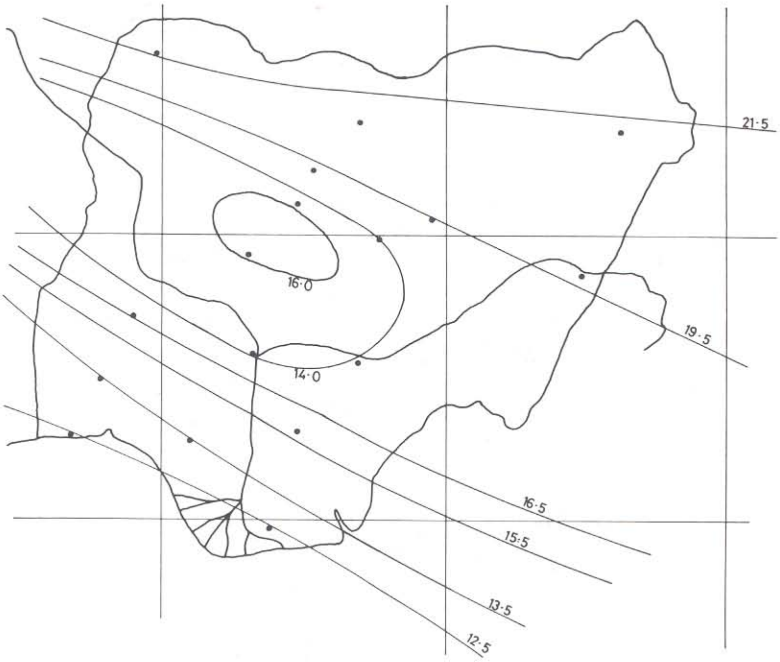

Fig. 7. Radiation isolines for Nigeria in the month of July (MJ/m^2-day).

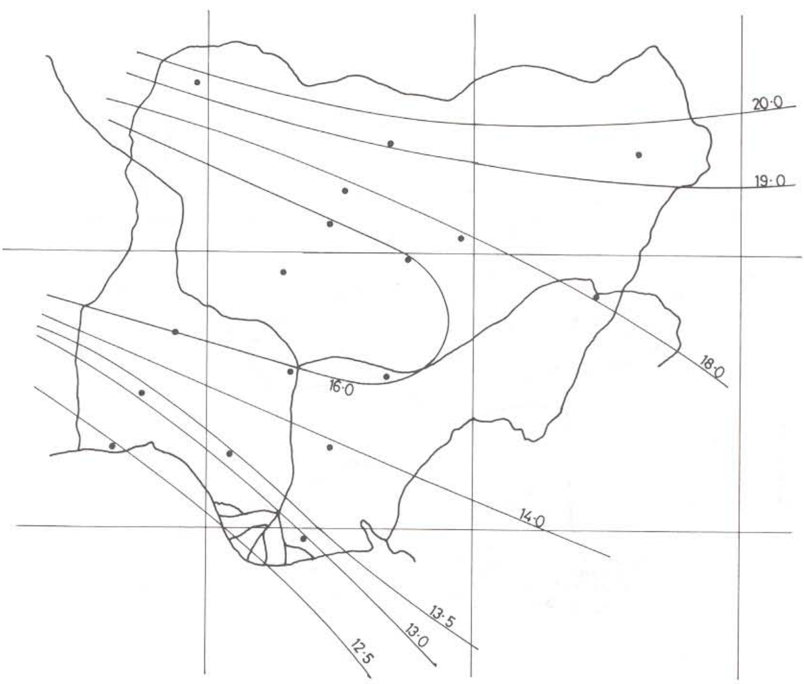

Fig. 8. Radiation isolines for Nigeria in the month of August (MJ/m^2-day).

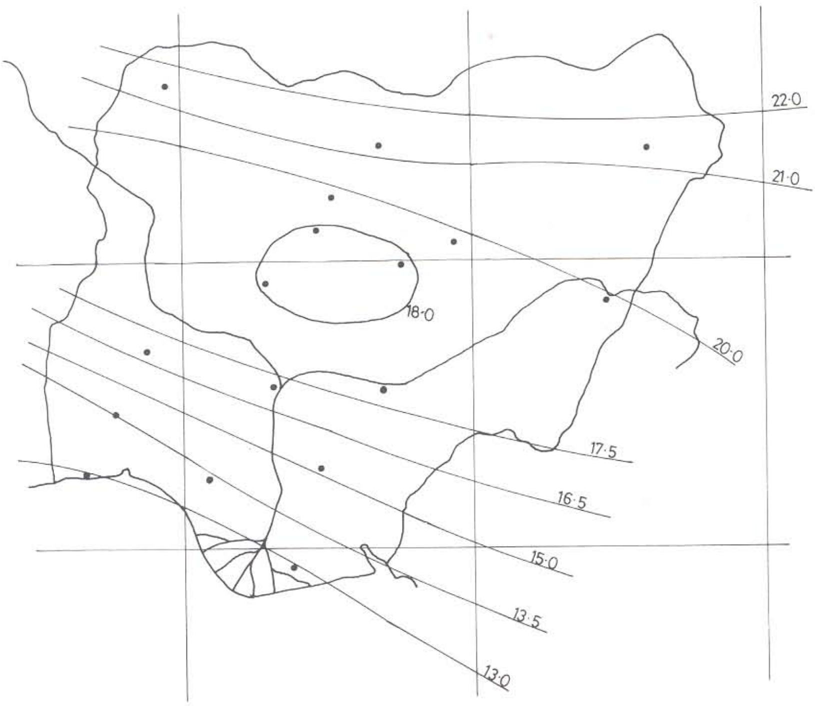

Fig. 9. Radiation isolines for Nigeria in the month of September (MJ/m²-day).

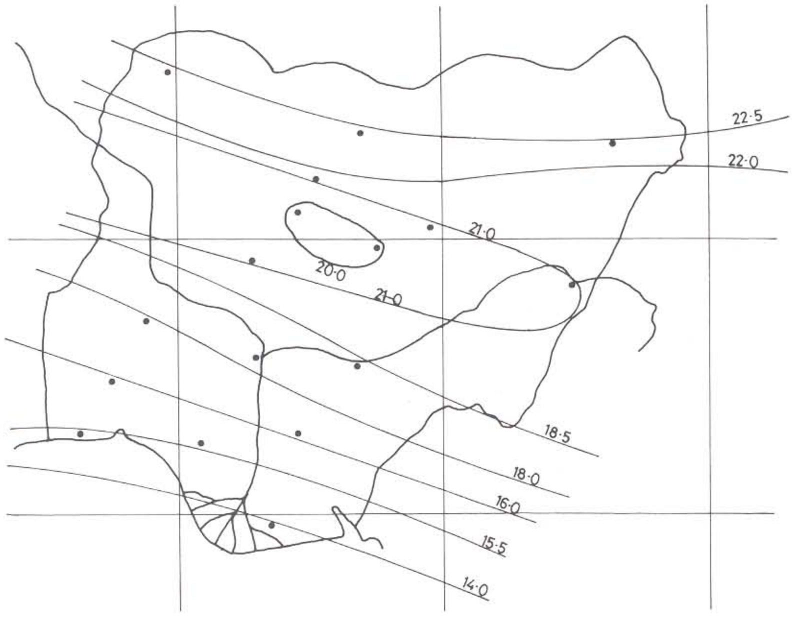

Fig. 10. Radiation isolines for Nigeria in the month of October (MJ/m²-day).

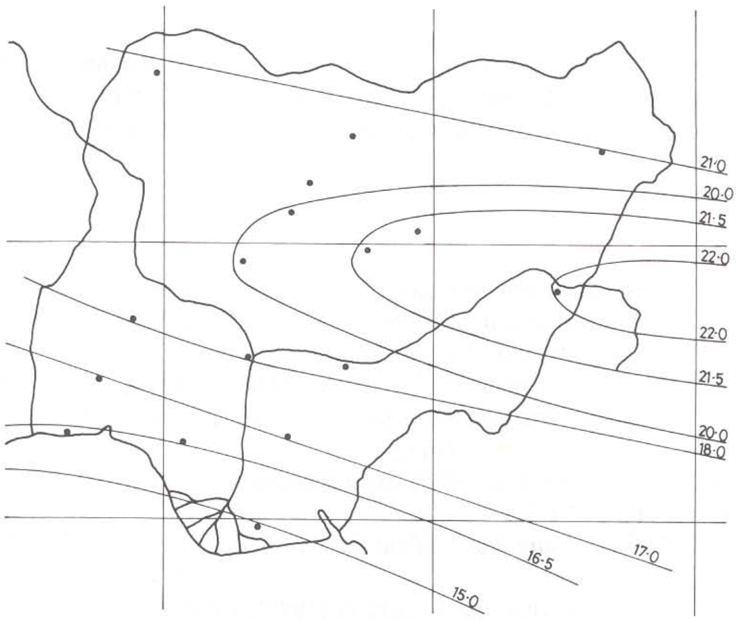

Fig. 11. Radiation isolines for Nigeria in the month of November (MJ/m^2-day).

NOMENCLATURE

A	Factor in the modified equation of Sabbagh et al.
a,b	Climatologically determined regression constants in the Page equation
C	Cloud amount, oktas
D	Mean daily hours of bright sunshine relative to 12 hours
j	Index of month of the year; j = 1, 2, --- for Jan, Feb, ---, etc.
K	$(\lambda N + w_{i,j} \cos L)10^2$ in the equation of Sabbagh et al.
L	Location latitude in radians
N	Mean length of the day during the month
H, H_o	Monthly mean daily horizontal total and extraterrestrial solar radiation respectively, g-cal/(cm^2-day) or MJ/(m^2-day)
Q	Monthly mean daily total solar radiation, MJ/(m^2-day)
R	Relative humidity
S	Relative sunshine, per cent of maximum possible sunshine hours
t	Maximum air temperature, °C
$w_{i,j}$	Reddy seasonal factor
α	Factor in the empirical equation of Sabbagh et al.
$\delta_1,\delta_2,\delta_3$	Factors in the equation of Sabbagh et al.
ϕ	Location latitude in degrees
λ	$0.2/(1 + 0.1\phi)$

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