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Estimation of incoming global solar radiation and its diffuse component at the surface in Paraiba state (NE Brazil)

K. Karuna Kumar(*), T. V. Ramana Rao, Carlos A. C. dos Santos and Alexandre M. T. de Medeiros

Department of Atmospheric Sciences, Federal University of Campina Grande Campina Grande, Brazil

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Summary. — Results of a study on the estimation of mean monthly values of incoming global solar radiation and its diffuse component at some stations in Paraiba state (NE Brazil) are presented in this paper. Radiation data at four stations is used. Ångström-type equations are derived for the estimation of global radiation and the diffuse fraction of global radiation is expressed in terms of the clearness index and the sunshine ratio. The applicability of previously reported equations for stations in this region is investigated.

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1. – Introduction

Solar radiation incident on the Earth's surface is an important parameter in meteorological, agricultural and climatological studies. However, many locations lack the necessary equipment for solar radiation measurement. By contrast data on sunshine is available for hundreds of stations in many countries. Numerous attempts have been made to estimate global radiation using sunshine data. The first correlation proposed for estimating monthly mean (daily) global radiation is due to Ångström [1].

$$R_1/R_c = a_1 + b_1(n_1/N_1), \tag{1}$$

where: R_1 is the monthly average daily global radiation reaching the measurement station, R_c the perfectly clear sky day horizontal insolation, n_1 the monthly average number of instrument —recorded bright sunshine hours per day, N_1 the average day length measured in hours, and the ratio n_1/N_1 gives the measure of the monthly mean daily fraction of possible sunshine.

(*) E-mail: karuna@dca.ufcg.edu.br

In eq. (1), parameters a_1 and b_1 are determined as best-fit shape parameters of the correlation found from the observational data.

Prescott [2] has modified such an insolation-sunshine correlation, by normalizing the ground-level insolation data to the extraterrestrial radiation, since the latter quantity can be more easily computed. Thus, he proposed the following equation:

$$R/R_T = a + b(n/N), \tag{2}$$

where R and R_T are the monthly mean daily values of global radiation on a horizontal plane at the surface and extraterrestrial solar radiation, respectively, and n and N are the corresponding values of instrument-measured sunshine hours and maximum possible hours per day, respectively, while a and b are constants which can be calculated from field measurements.

Although several other expressions which include more parameters (latitude, altitude etc) have been suggested by different authors [3, 4] eq. (1) has been found to be very convenient, applicable to a large number of stations and is the most widely used correlation [5-9].

Availability of solar radiation data is a basic necessity for the design of energy conversion devices. In assessing the performance of systems utilizing solar energy an important input parameter is the diffuse solar radiation on a horizontal surface at the location of interest. Diffuse solar radiation is still measured at only a few locations. In developing countries this dearth is even more acute. A series of empirical correlations have been suggested for the estimation of the diffuse fraction of global radiation [10-13].

Results of a study on the estimation of global radiation and the diffuse fraction of global radiation at four stations in Paraiba state in NE Brazil are presented in this paper. Location of the stations is shown in fig. 1.

Global radiation and diffuse solar radiation were measured with Fuess bimetallic actinographs. Sunshine was measured with Campbell-Stokes sunshine recorders. The actinograph is associated with an accuracy of 5% [14]. Despite a somewhat slower response, their accuracies are compatible with second-class radiometers [15]. The duration of sunshine can be measured correctly up to 10 minutes as each sub-division is represented by 10 minutes. These instruments were calibrated every year by the staff of the Department of Atmospheric Sciences of the Federal University of Campina Grande. All the data used in this study was collected between 1980 and 2000.

Radiation data measured at Barra de Santa Rosa are available for more years than at the other stations. The data recorded at this station have been analyzed to derive equations suitable for estimating the global solar radiation and its diffuse fraction, and testing the validity of such equations at the other stations. The applicability of previously reported equations for stations in this region is verified.

2. – Methodology

The extraterrestrial solar radiation is computed using the equation

$$R_T = \frac{24}{\pi} I_{\mathrm{sc}} \cdot E_0 \left[\sin\phi \cdot \sin\delta \left(\frac{W_s \pi}{180} \right) + \cos\phi \cdot \cos\delta \cdot \sin W_s \right], \tag{3}$$

where I_{sc} is the solar constant ($4921\,\mathrm{KJ\,m^{-2}\,h^{-1}}$) and ϕ is the latitude. The eccentricity factor (E_0), solar declination (δ) and the sunset hour angle (W_s) are computed from the

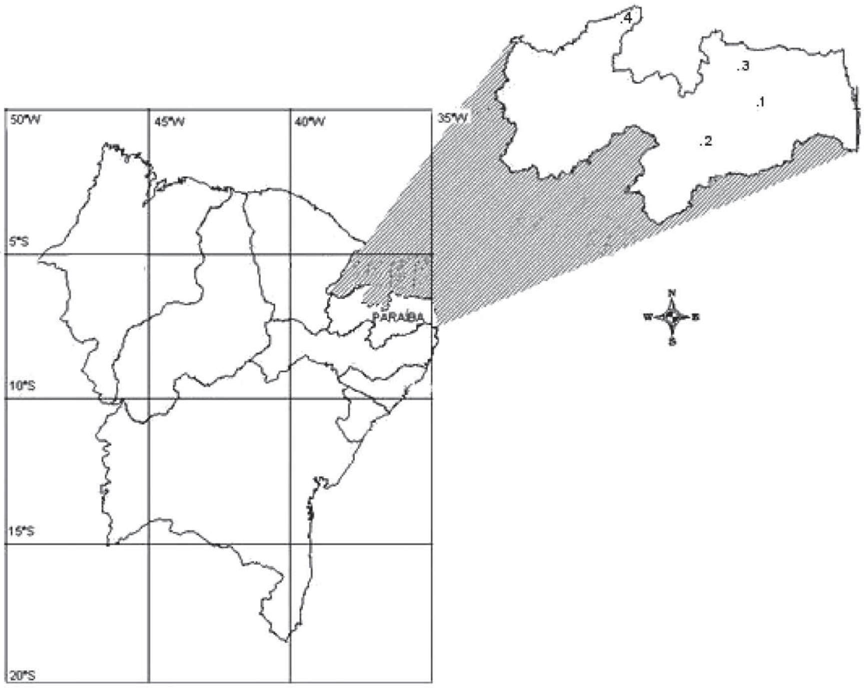

Fig. 1. – Location of stations: 1. Campina Grande (7° 13′ S; 35° 52′ W; 508 m), 2. Cabaceiras (7° 30′ S; 36° 17′ W; 390 m); 3. Barra da Santa Rosa (6° 43′ S; 36° 4′ W; 440 m); 4. Belém do Brejo Cruz (6° 11′ S; 37° 32′ W; 190 m).

following expressions:

$$E_0 = 1 + 0.033 \cdot \cos\left(\frac{360 N_\mathrm{d}}{365}\right) \tag{4}$$

and

$$\delta = 23.45 \cdot \sin\left[\frac{360}{365}\big(284 + N_\mathrm{d}\big)\right] \tag{5}$$

in which

$$W_s = \cos^{-1}[-\tan\phi \cdot \tan\delta] \tag{6}$$

and N_d is the day number.

The maximum possible sunshine (N) in hours is given by

$$N = \frac{2}{15}\cos^{-1}[-\tan\phi \cdot \tan\delta] = \frac{2W_s}{15}\,. \tag{7}$$

Daily values of global radiation (R) and sunshine (n) at Barra de Santa Rosa during the period 1975-1994 are used in this study. For each day of the year R_T and N are computed. Monthly mean values of the parameters R/R_T and n/N for ten years are used to derive the constants a and b fitting the Prescott [2] formula defined in eq. (2).

These constants are computed using two approaches.

In method A, 1) for each of the ten years a and b are derived using 12 monthly mean values of R/R_T and n/N and 2) from the ten sets of a and b thus obtained, mean values of a and b are computed.

In method B, 1) for each month of the year a and b are derived using ten monthly mean values of R/R_T and n/N and 2) from the 12 sets of a and b obtained, mean values of a and b are derived.

Using the values of a and b thus obtained, mean monthly values of global radiation at the station are calculated and compared with observed values. In each case Mean Bias Error (MBE), Mean Percentage Error (MPE) and the Root Mean Square Error (RMSE) are calculated.

Radiation and sunshine data at the station is used to test the applicability of previously reported correlations.

Samuel [16] used radiation and sunshine data at four stations in Sri Lanka and derived the following expression for the estimation of global radiation:

$$R = R_T \left(a_1 + b_1 \frac{n}{N} \right), \tag{8}$$

where

$$a_1 = -0.14 + 1.2 \left(\frac{n}{N} \right) - 0.82 \left(\frac{n}{N} \right)^2, \qquad b_1 = 1.32 - 2.89 \left(\frac{n}{N} \right) + 2.24 \left(\frac{n}{N} \right)^2.$$

Bahel *et al.* [17] proposed the equation

$$R = R_T \left(0.175 + 0.552 \frac{n}{N} \right). \tag{9}$$

These two equations have been used by several authors for the estimation of global radiation [9, 18, 19].

Rietveld [20] examined a large set of best-fit values of a and b, found in the literature, and noted that parameter a is related linearly and parameter b hyperbolically to the appropriate mean value of n/N, defining the following general relationship:

$$R/R_T = a + b(n/N), \tag{10}$$

which has been subsequently employed to a large extent in the literature to derive average estimates of global insolation from sunshine data.

Daily values of global radiation (R), diffuse solar radiation (R_s) and sunshine (n) at Barra de Santa Rosa during nine years are used to derive equations relating the diffuse fraction of global radiation to the clearness index K_T ($K_T = R/R_T$) and the sunshine ratio (n/N). The validity of the equations is tested for Barra da Santa Rosa and Campina Grande in Paraiba state (NE Brazil). The results are compared with those based on correlations reported by other investigators.

TABLE I. – *Observed and estimated values of global radiation at Barra de Santa Rosa* ($MJ\,m^{-2}\,d^{-1}$).

Month	R_T	n/N	R_{Obs}	R_{Est}				
				Bahel eq. (9)	Samuel eq. (8)	Rietveld eq. (10)	eq. (11)	eq. (12)
Jan.	37.8	0.63	18.4	19.76	20.0	21.6	18.9	19.0
Feb.	38.3	0.60	19.0	19.38	19.84	21.1	18.8	18.9
Mar.	37.9	0.55	18.3	18.14	18.88	19.7	18.1	18.2
Apr.	36.0	0.53	17.0	16.83	17.65	18.3	17.0	17.0
May	33.5	0.49	15.6	14.92	15.9	16.2	15.5	15.5
June	32.0	0.47	14.1	13.9	14.9	15.0	14.6	14.6
July	32.6	0.46	14.3	13.98	15.08	15.1	14.8	14.8
Aug.	35.2	0.55	16.6	16.8	17.5	18.3	16.8	16.8
Sep.	37.3	0.63	18.0	19.5	19.77	21.3	18.6	18.7
Oct.	38.3	0.71	20.3	21.71	21.50	23.7	20.0	20.1
Nov.	38.0	0.71	19.6	21.54	21.35	23.6	19.8	20.0
Dec.	37.5	0.67	19.0	20.43	20.47	22.3	19.1	19.3
MPE				4.4	5.9	12.0	1.6	1.8
MBE				0.56	1.05	2.2	0.15	0.23
RMSE				1.03	1.15	2.45	0.34	0.38

3. – Results

3˙1. *Estimation of global radiation.* – Using radiation and sunshine data recorded over a ten-year period, the constants a and b of Ångström's equation are obtained through standard regression techniques. Using the methods A and B, the following equations were found for monthly mean global radiation R:

$$R = R_T\left(0.33 + 0.27\frac{n}{N}\right) \tag{11}$$

and

$$R = R_T\left(0.32 + 0.29\frac{n}{N}\right), \tag{12}$$

respectively.

Measured and estimated global radiation values are given in table I. Values of R based on the equations of Samuel [16], Bahel *et al.* [17] and Rietveld [20] are also included in table I.

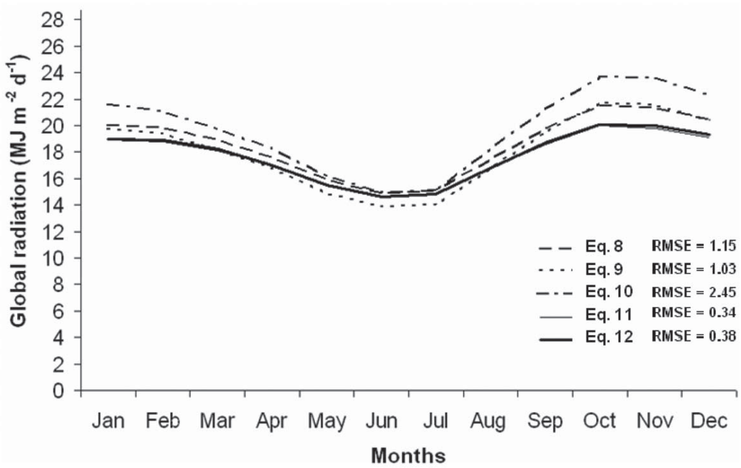

Fig. 2. – Estimated global radiation values at Barra de Santa Rosa.

The five models are evaluated in terms of Mean Bias Error (MBE), Root Mean Square Error (RMSE) and the Mean Percentage Error (MPE).

$$\text{MBE} = \frac{\sum_{i=1}^{n}(x_{ie} - x_{im})}{n}, \tag{13}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(x_{ie} - x_{im})^2}{n}}, \tag{14}$$

$$\text{MPE} = \frac{\sum_{i=1}^{n}\left[\frac{(x_{ie} - x_{im})}{x_{im}} \cdot 100\right]}{n}. \tag{15}$$

In these expressions x_{ie} and x_{im} are the i-th estimated and measured values and n is the number of observations, respectively. A positive value of MBE suggests an overestimation and a negative value an underestimation by the model. The values of MBE represent a systematic error or bias while the RMSE represents a non-systematic error. In the case of MPE the signs of the errors are neglected and the percentage errors are added up to derive the mean value. For a model to be a good estimator MPE, MBE and the RMSE should be small.

From table I, it can be seen that eq. (10) estimates global radiation at the station with much precision, the mean error being 1.6%. The models of Samuel [16] and Bahel *et al.* [17] provide R-values with a mean error of about 5%. The extensively used model of Rietveld gives poor results with a mean error of 12%.

The variation during the year of estimated global radiation values at Barra de Santa Rosa is shown in fig. 2. For all the curves, maximum values occurred in October and the minimum values in June.

A preliminary study of available radiation data at locations in Paraiba state suggests that eq. (10) can be used for the estimation of global radiation at other stations in the

TABLE II. – *Observed and estimated values of global radiation at three stations in Paraiba state (*$MJ\,m^{-2}\,d^{-1}$*).*

	Campina Grande				Cabaceiras				Belem do Brejo Cruz			
Month	R_{Obs}	R_T	n/N	R_{Est}	R_{Obs}	R_T	n/N	R_{Est}	R_{Obs}	R_T	n/N	R_{Est}
Jan.	18.6	37.9	0.64	19.0	20.0	38.0	0.69	19.6	19.1	37.6	0.63	18.8
Feb.	19.1	38.4	0.59	18.8	19.7	38.4	0.61	19.0	19.6	38.2	0.61	18.9
Mar.	19.0	37.8	0.56	18.2	20.0	37.8	0.64	19.0	19.6	37.9	0.64	19.1
Apr.	17.5	35.8	0.53	16.9	17.8	35.8	0.58	17.4	19.1	36.2	0.64	18.2
May	15.0	33.4	0.47	15.2	16.0	33.2	0.55	15.9	17.1	33.7	0.64	16.9
June	13.3	31.8	0.40	13.9	13.8	31.7	0.46	14.4	16.0	32.3	0.62	16.0
July	13.7	32.4	0.39	14.1	13.8	32.3	0.45	14.6	17.1	32.9	0.65	16.6
Aug.	16.7	34.9	0.54	16.6	16.6	35.1	0.59	17.2	19.2	35.1	0.73	18.5
Sep.	18.2	37.3	0.58	18.2	18.4	37.2	0.61	18.4	20.8	37.3	0.75	19.9
Oct.	20.0	38.4	0.66	19.5	20.7	38.4	0.71	20.0	21.8	38.3	0.80	20.9
Nov.	19.9	38.2	0.69	19.7	21.1	38.2	0.72	20.0	20.8	37.9	0.78	20.5
Dec.	18.2	37.7	0.62	18.7	20.1	37.8	0.68	19.4	19.8	37.3	0.75	19.9
MPE	2.2				3.2				2.5			
MBE	−0.03				−0.26				−0.5			
RMSE	0.44				0.67				0.59			

region. Measured and estimated mean monthly values of global radiation at Campina Grande, Cabaceiras and Belem de Breza de Cruz are presented in table II. The mean percentage errors are between 2 and 3% and the mean bias error and the root-mean-square error are quite small.

Measured and estimated values of global radiation at the three stations are depicted in fig. 3. For all the curves minimum values are noticed in June. Monthly mean values of global radiation measured at the stations varied between 13.3 and 21.8 $MJ\,m^{-2}\,d^{-1}$.

3·2. *Diffuse solar radiation.* – Climatological mean monthly values of some radiation quantities and related ratios at Barra de Santa Rosa are presented in table III.

Mean monthly values of radiation parameters presented in table I are based on data for all the years of the study period (1975-1994). Diffuse solar radiation at the station is available during 16 years of the study period and for seven of these the data is missing for some months of the year. The values given in table III are hence based on daily values for 9 years. For this reason slight differences exist in the mean monthly values of R and n/N for corresponding months in tables I and III.

The above consideration also applies to the small differences between values of R and n/N at Campina Grande given in table II and those in tables V and VI.

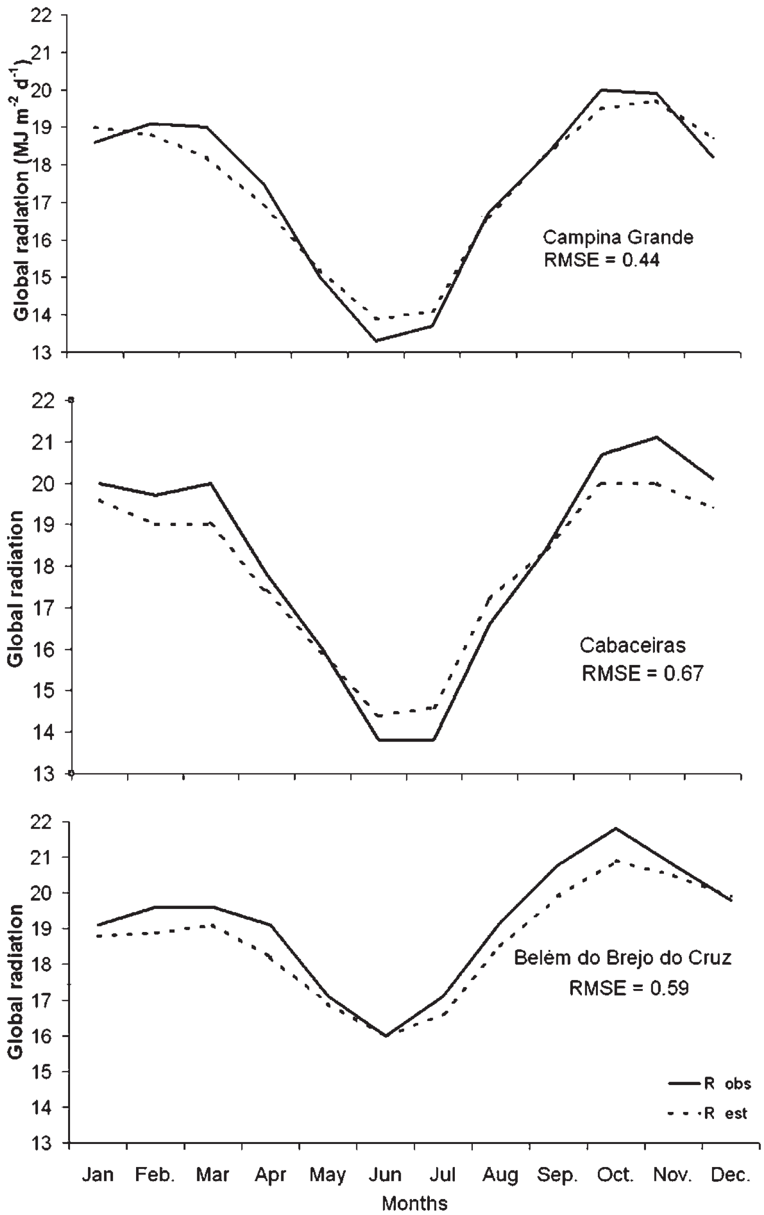

Fig. 3. – Monthly mean values of observed and estimated global radiation at Campina Grande, Cabaceiras and Belém do Brejo do Cruz.

Using daily values of the radiation parameters determined at Barra de Santa Rosa during nine years, the following relationship is derived between R_s/R and the clearness index K_T:

$$R_s/R = 1.06 - 1.386K_T. \tag{16}$$

TABLE III. – *Radiation data at Barra de Santa Rosa (6° 43′ S 36° 03′ W).*

Month	R	R_s	R_T	R/R_T	n	N	n/N	R_s/R
Jan.	18.0	7.4	37.8	0.477	7.32	11.65	0.63	0.41
Feb.	18.8	7.6	38.3	0.490	7.09	11.78	0.60	0.40
Mar.	18.2	7.1	37.9	0.481	6.75	11.96	0.56	0.39
Apr.	16.7	6.6	36.0	0.464	6.43	12.14	0.53	0.39
May	15.8	6.2	33.5	0.470	6.33	12.30	0.51	0.40
June	14.0	6.3	32.0	0.437	5.73	12.38	0.46	0.45
July	14.4	6.6	32.6	0.441	5.78	12.35	0.47	0.46
Aug.	16.9	6.5	35.2	0.480	6.98	12.20	0.57	0.38
Sep.	18.1	6.9	37.3	0.484	7.61	12.03	0.63	0.38
Oct.	20.3	6.7	38.3	0.531	8.44	11.84	0.71	0.33
Nov.	19.3	7.2	38.0	0.507	7.99	11.68	0.68	0.37
Dec.	18.5	7.1	37.5	0.494	7.51	11.61	0.65	0.38

Values of R_s/R derived from the above equation are given in table IV, together with the measured values.

Liu and Jordan [10] developed a statistically based correlation from results obtained from a single station Blue Hill MA. Klein [21] developed the following mathematical expression for the correlation:

$$R_s/R = 1.390 - 4.027K_T + 5.531{K_T}^2 - 3.108{K_T}^3 \,. \tag{17}$$

Page [11] developed correlations between daily total and diffuse radiation for ten widely spread stations in the 40° N–40° S latitude belt, and obtained the following linear relationship:

$$R_s/R = 1.00 - 1.13K_T. \tag{18}$$

Gopinathan [22] derived an expression for R_s/R as a function of both the clearness index and the sunshine ratio. The equation

$$R_s/R = 0.879 - 0.575K_T - 0.323(n/N) \tag{19}$$

was found to provide good estimates of diffuse solar radiation for stations in South Africa.

Values of R_s/R based on eqs. (16), (17) and (18) are included in table IV. Mean Percentage Error (MPE), Mean Bias Error (MBE) and the Root Mean Square Error (RMSE) in table IV show that eq. (15) estimates diffuse solar radiation with more precision than the other equations.

While the work of Liu and Jordan [10] is based on data from a single location it has been found to yield good results in different locations in the world. In the present case

TABLE IV. – *Observed and estimated values of diffuse fraction of global radiation at Barra de Santa Rosa.*

		$(R_s/R)_{\text{Est.}}$				
Month	$(R_s/R)_{\text{Obs}}$	Liu and Jordon eq. (17)	Gopinathan eq. (19)	Page eq. (18)	eq. (16)	eq. (20)
Jan.	0.41	0.39	0.40	0.46	0.40	0.37
Feb.	0.40	0.38	0.40	0.45	0.38	0.38
Mar.	0.39	0.39	0.42	0.46	0.39	0.39
Apr.	0.39	0.40	0.44	0.48	0.41	0.40
May	0.40	0.40	0.44	0.47	0.40	0.41
June	0.45	0.43	0.48	0.51	0.45	0.43
July	0.46	0.42	0.47	0.50	0.45	0.43
Aug.	0.38	0.39	0.42	0.46	0.39	0.39
Sep.	0.38	0.38	0.40	0.45	0.39	0.37
Oct.	0.33	0.35	0.34	0.40	0.32	0.34
Nov.	0.37	0.36	0.37	0.43	0.36	0.35
Dec.	0.38	0.38	0.39	0.44	0.38	0.37
MPE		3.1	5.3	16.5	2.1	3.9
MBE		−0.01	0.02	0.06	0.0	−0.01
RMSE		0.02	0.03	0.07	0.01	0.02

their equation provides better estimates of R_s/R than that of Gopinathan (1988). The Page [11] relationship in eq. (17) cannot be used at this location though it has been extensively used in the literature [12, 23-25].

The linear relationship between the ratio R_s/R and the sunshine ratio n/N was obtained from eqs. (11) and (16).

$$R_s/R = 0.6 - 0.37n/N. \tag{20}$$

Values of R_s/R based on eq. (19) given in table IV show that this equation provides nearly as good estimates as that of Liu and Jordan [10]. It may be mentioned here that eq. (15) needs only global radiation data, while eq. (19) needs global radiation and sunshine.

The variation during the year of observed and estimated values of R_s/R at Barra de Santa Rosa is shown in fig. 4.

Using radiation data at Campina Grande (table V) monthly mean values of R_s/R are computed using eqs. (15) and (19) and the results are compared with measured values (table VI). Values of MPE, MBE and RMSE are similar to those determined for the data set relative to the Barra de Santa Rosa station, and it seems likely that the equations for

TABLE V. – *Radiation data at Campina Grande (7°13′ S, 35°53′ W).*

Month	R	R_s	R_T	R/R_T	R_s/R_T	n	N	n/N	R_s/R
Jan.	18.5	7.2	37.9	0.488	0.191	7.39	11.62	0.64	0.39
Feb.	19.0	7.5	38.4	0.494	0.195	7.00	11.76	0.60	0.39
Mar.	19.0	6.9	37.8	0.502	0.181	6.75	11.95	0.57	0.36
Apr.	17.0	6.4	35.8	0.475	0.179	5.97	12.17	0.49	0.38
May	15.0	6.2	33.4	0.449	0.185	5.83	12.32	0.47	0.41
June	13.0	6.1	31.8	0.408	0.192	4.63	12.41	0.37	0.47
July	13.3	6.3	32.4	0.410	0.195	4.39	12.37	0.36	0.47
Aug.	16.5	6.5	34.9	0.473	0.185	6.27	12.22	0.51	0.39
Sep.	17.8	6.9	37.3	0.477	0.186	6.89	12.03	0.57	0.39
Oct.	19.6	6.8	38.4	0.510	0.178	7.89	11.83	0.67	0.35
Nov.	19.2	7.2	38.2	0.503	0.190	7.83	11.66	0.67	0.38
Dec.	18.6	7.0	37.7	0.493	0.185	7.60	11.58	0.66	0.38

TABLE VI. – *Observed and estimated values of diffuse fraction of global radiation at Campina Grande.*

Month	R/R_T	n/N	$(R_s/R)_{\text{Obs}}$	$(R_s/R)_{\text{Est}}$ eq. (15)	$(R_s/R)_{\text{Est}}$ eq. (19)
Jan.	0.488	0.64	0.39	0.38	0.36
Feb.	0.494	0.60	0.39	0.38	0.38
Mar.	0.502	0.57	0.36	0.36	0.39
Apr.	0.475	0.49	0.38	0.40	0.42
May	0.449	0.47	0.41	0.44	0.42
June	0.408	0.37	0.47	0.49	0.46
July	0.410	0.36	0.47	0.49	0.47
Aug.	0.473	0.51	0.39	0.40	0.41
Sep.	0.477	0.57	0.39	0.40	0.39
Oct.	0.510	0.67	0.35	0.35	0.35
Nov.	0.503	0.67	0.38	0.36	0.35
Dec.	0.493	0.66	0.38	0.38	0.36
MPE				3	4.3
MBE				0.01	0.0
RMSE				0.02	0.02

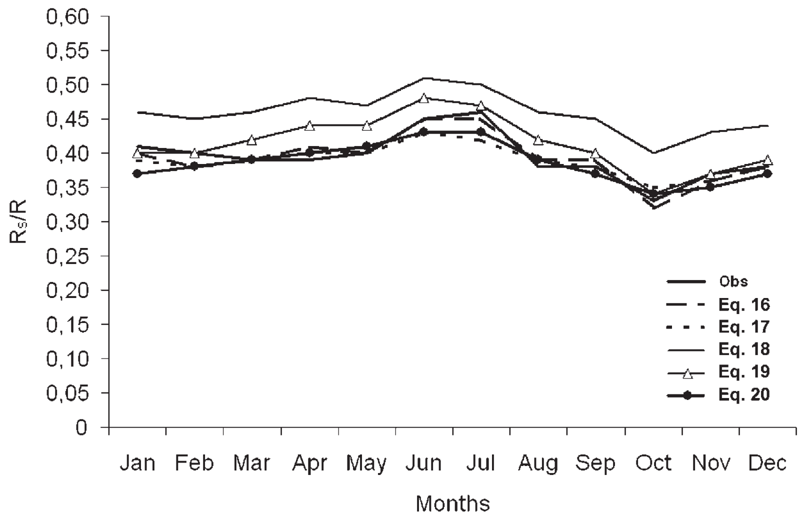

Fig. 4. – Observed and estimated values of R_s/R at Barra de Santa Rosa.

the estimation of global radiation and the diffuse fraction of global radiation obtained in this study are valid at other stations in the Paraíba state.

4. – Conclusions

In this study estimated monthly mean values of global radiation and diffuse solar radiation at some stations in NE Brazil are compared with measured values. Ångström-type equations are used for the estimation of global radiation and diffuse solar radiation is derived from the clearness index and the sunshine ratio.

The mean percentage errors in the estimation of global radiation varied between 1.6% and 3.2%. Values of MPE, MBE and RMSE for the stations are significantly less than those reported in several studies [8, 9, 18, 19]. An interesting feature noticed is that the widely used expression of Rietveld [20] is not valid in this region.

It is found that diffuse solar radiation can be estimated with much accuracy using the clearness index. In this case also, the most widely used equation, that due to Page [11], is not applicable in this region. The diffuse fraction of global radiation can be estimated from the sunshine ratio with a mean percentage error of about 4%. Similar results have been reported by Nagaraja Rao *et al.* [26] and by Sears *et al.* [27].

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