A SIMPLE METHOD FOR THE ESTIMATION
OF GLOBAL SOLAR RADIATION OVER NORTHEAST BRAZIL[1]

S. JEEVANANDA REDDY[2], MALAQUIAS DA SILVA AMORIM NETO[3]
e MARIA DA GLÓRIA DA SILVA ELPÍDIO[4]

ABSTRACT - This paper presents a simple method for estimating the global solar radiation over northeast Brazil. The inputs into the model are easily measurable (and available for a wide network of stations) meteorological parameter, namely precipitation and latitude. The comparison between observed and predicted values present a good agreement.

Index terms: turbidity, meteorological parameter, precipitation, latitude.

MÉTODO SIMPLES PARA ESTIMAR A RADIAÇÃO SOLAR GLOBAL NO NORDESTE DO BRASIL

RESUMO - Este trabalho apresenta um simples método para estimar a radiação solar global sobre o Nordeste do Brasil. Os inputs são parâmetros meteorológicos facilmente mensuráveis (e disponíveis para rede de estações), isto é, precipitação e latitude. A comparação entre os valores observados e estimados apresenta boa concordância.

Termos para indexação: turbidez, parâmetros meteorológicos, precipitação, latitude.

INTRODUCTION

Among the several climatic parameters, global solar radiation plays an important role in the crop production. Over northeast Brazil is being measured at about 50 locations (Vieira et al. 1981). This network constitutes less than 5% of precipitation stations. These records are available only for few recent years. Barbaro et al. (1978) state that over Italy, based on the level of calibration, the intrumental errors range from 3 to 10%. Because of these constraints, in the past several scientists used simple models to derive global solar radiation for a wide network of stations from other meteorological parameters (Reddy 1971, Reddy & Rao 1973, Reddy et al. 1977, Angstrom 1924).

Goldberg et al. (1979) state that "over years there have been many attempts to produce models which can predict the amount of solar radiation energy available at any location. These models have ranged in complexity from the radiative transfer functions of Chandrasekar to some simple models which do not require massive computers". They tested four such simple models (Liu & Jordan 1963, Goldberg & Klein 1978, Reddy 1971, Barbaro et al. 1978). Hutchinson et al. (1983) reviewed the methods used in Australia. The widely quoted model in the literature is that of Angstrom (1924). His equation received widest prominence because of its critical position in Penman's (1948) evaporation/or evapotranspiration formulae. Linacre (1967), and Afonso & Santos (1980) presented a detailed list of constants in Angstrom's equation obtained by different authors over different parts of the world. Vieira et al. (1981) presented these constants for each month for 50 locations over northeast Brazil. These studies indicate that there is no consistency in these parameters either with latitude or with cloud cover. Glover & McCulloch (1958) suggested a latitude correction which was later adopted by FAO (Frère 1978).

Reddy (1971, 1981), Reddy & Rao (1973) and Reddy et al. (1977) presented simple empirical formulae. The first two were used in presenting global solar radiation over India (Reddy & Rao 1976) and Mexico (Almonza & Lopez 1978), while the third one was used in the analysis of longterm trend in radiation over few selected locations in India.

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2 Consultant (Agroclimatology), CPTASA/EMBRAPA/IICA.

3 (Agroclimatologist), CPATSA/EMBRAPA.

4 Assistant (Statistics), CPATSA/EMBRAPA, C.P. 23, Petrolina (PE), Brazil, 56300.

The basic weakness of empirical formulae is that they don't account for the localized factors that contribute significantly to the level of turbidity that increases or decreases the proportionate radiation per unit cloud cover. Therefore, it is very important to test the models before they are actually applied to any new region (Sabbagh et al. 1977).

The objective of this study, therefore, is to test some of these models and suggest suitable method for the estimation of global solar radiation as applicable to northeast Brazil.

Data

The primary data consist of observed global solar radiation for 38 locations (Table 1, Fig. 1) over northeast Brazil (Vieira et al. 1981) and for

TABLE 1. List of locations used in the analysis.

Station	Latitude o	Latitude '	Longitude o	Longitude '	Altitude m	Period of data
Acaraú	02	53	40	07	-	1976-78*
Areia	06	58	35	41	606	1969-77
Barbalha	07	19	39	18	408	1970-77
Barra do Corda	05	30	45	16	082	1970-78
Barreiras	12	08	45	00	441	1969-78
Bom Jesus da Lapa	13	16	43	25	441	1969-78
Cabrobó	08	31	39	18	325	1970-78
Caetité	14	04	42	28	878	1969-78
Campina Grande	07	13	35	53	526	1971-78
Caravelas	17	44	39	15	004	1969-78
Carolinas	07	20	47	28	185	1969-79
Crateús	05	11	40	40	277	1970-78
Cruzeta	06	26	36	47	266	1971-78
Floriano	06	46	43	02	123	1969-78
Fortaleza	03	43	38	28	027	1969-78
Iguatu	06	22	39	18	212	1970-78
Ilhéus	14	47	39	03	066	1969-78
Imperatriz	05	34	47	35	124	1976-79*
Irecê	11	18	41	54	747	1971-78
Jaguaruana	04	50	37	48	013	1969-78
João Pessoa	07	07	34	53	030	1971-77
Lençóis	12	34	41	23	528	1972-78
Macau	05	07	36	38	-	1973-78
Maceió	09	40	35	43	046	1976-78*
Monte Santo	10	26	39	20	545	1970-78
Morada Nova	05	06	38	23	-	1970-78
Patos	07	00	37	18	249	1974-78*
Petrolina	09	23	40	30	372	1970-78
Propriá	10	13	36	51	035	1969-78
Quixeramobim	05	12	39	18	211	1969-78
Recife	08	03	34	55	018	1968-78
Salvador	13	00	38	31	046	1969-78
São Gonçalo	06	45	38	13	235	1971-78
São Luiz	02	32	44	17	036	1970-79
Sobral	03	42	40	21	084	1970-78
Surubim	07	50	35	46	-	1972-78
Teresina	05	05	42	49	079	1976-78*
Turiaçu	01	43	45	24	008	1976-79*

* Period of data ≤ 5 years.

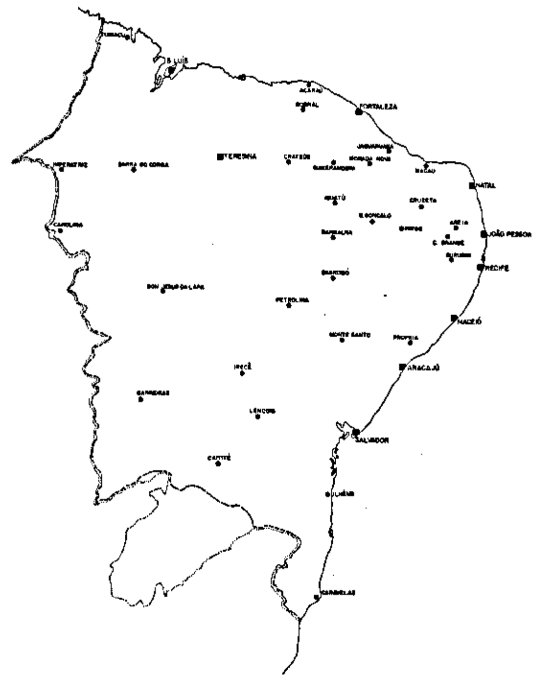

FIG. 1. List of locations used in this study.

few selected locations the sunshine and the temperature data (Brasil. SUDENE 1970). The precipitation data are taken from Hargreaves (1974) publication, for the above 38 locations.

MODEL DEVELOPMENT

Comparison of different methods

The following models are tested to understand their suitability to northeast Brazil:

a. Angstrom (1924) model as adopted by FAO (Frère 1978):

$$R_{t1} = Q_o \left[a + b\,(n/N)\right] \quad (1)$$

b. Reddy (1971) and Reddy & Rao (1973) model:

$$R_{t2} = K \left[1.0 + 0.8\, n/N\right] \left[1 - 0.2\, r/M\right] / 0.1\sqrt{h} \quad (2)$$

Reddy (1981) suggested a modification to K as:

$K = K \times N/12$

Reddy (1974) also suggested a method for estimating - n through cloud amount data.

c. Reddy et al. (1977) model:

$$R_{t3} = a \left[\frac{1013.2}{p}\right]^{1.5 \log \phi} \left[\frac{N}{12,5}\right] \sqrt{e_s} \quad (3)$$

Where: R_{ti} = global solar radiation estimated using equation i (i = e s. 1, 2, 3, respectively), cal/cm^2/day.
Q_o = theoretical solar radiation on the top of the atmosphere, cal/cm^2/day.
n = bright sunshine, hours/day.
N = day length, hours
h = relative humidity, %
r = rainy days in a month, days
M = number of days in a calender month, days.
e_s = saturation vapour pressure, mbar.

$$= \text{Exp}\,(54.878919 - \frac{6790.4985}{T} - 5.02808 \log_e T)$$

T = everage temperature, ^{O}A
P = station level pressure, mbar.
ϕ = latitude of the place, degrees.
K,a,b = constants.

Eq. 1 considers the relative hours of bright sunshine, eq. 2, in addition, takes into account the relative humidity and rainy days and eq. 3, considers the average temperature, day length, station level pressure (i.e. height of the station) and latitude in the estimation of global solar radiation. In eq. 1 the regression constant "a" is multiplied by a latitude term (cos ϕ). For the comparison of these models the data of 15 - locations well distributed over northeast Brazil are used. Tables 2, 3 and 4 present the ratios of global solar radiation estimated (R_{ti}) respectively using eqs. 1, 2 and 3 to the observed (R_{to}), values [i.e., R_{ti}/R_{to} for i = to 3]

In the case of eqs. 2 and 3, the ratios present a systematic decrease with latitude (Tables 3 and 4). In the case of eq. 2 the ratios are very large (overestimate) in low latitudes particularly in December and January. It is well known that the atmosphere over the tropics is generally more turbid than that over the temperate latitudes and this is more in Summer than in Winter. Angstrom (1961) found a decrease in turbidity with latitude. Turbidity increase with increasing precipitable water content (Yamamoto et al. 1968) and should be high at humid coastal stations - precipitable water content decrease with height. The former was accounted by a latitude term (cos ϕ) in the case of eq. 1. In the case of eq. 2, these were accounted by the terms K, h and r where K is different for coastal as well as elevated locations (Reddy & Rao 1973). Most of these are also accounted in eq. 3. However, the term K in eq. 2 appears to present an overestimate for regions below 8^{o} lat., as in the development of this formula the data for regions between 8 and 35^{o} lat. were only considered. In addition, it my be possible that the turbidity is greater over northeast Brazil compared to India (see Tables 2 and 4). The deviations obtained with eqs. 2 and 3 (Tables 3 and 4) can be adjusted by fitting the ratios to logarithm of latitude as they present a quite systematic decrease with latitude. This is not so systematic in eq. 1 (Table 2). In the case of eq. 3, it overestimates in Winter and underestimates in Summer

TABLE 2. Ratios of global solar radiation estimated using Eq. 1 to observed at 15 locations over northeast Brazil.

Station	Latitude (degrees)	R_{t1}/R_{t0}*											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Turiaçu	1.72	1.31	1.05	1.20	1.09	1.06	1.10	1.14	1.09	1.06	1.06	0.98	1.12
São Luiz	2.53	1.36	1.26	1.23	1.30	1.32	1.27	1.31	1.28	1.26	1.19	1.18	1.33
Sobral	3.70	1.03	0.94	0.93	0.93	0.96	0.96	0.99	0.99	0.97	0.96	0.93	0.95
Fortaleza	3.77	1.18	1.12	1.16	1.16	0.91	1.15	1.13	1.07	1.04	1.09	1.10	1.08
Terezina	5.08	1.16	1.06	0.96	0.88	1.05	1.08	1.07	1.05	1.05	1.07	1.08	1.03
Quixeramobim	5.20	1.10	1.08	1.01	1.06	1.14	1.15	1.14	1.10	1.10	1.11	1.08	1.09
Barra do Corda	5.50	1.12	1.06	1.06	1.08	1.10	1.10	1.11	1.15	1.14	1.16	1.12	1.13
Iguatu	6.37	1.03	1.09	1.00	0.98	1.06	1.04	1.09	1.06	1.06	1.08	1.11	1.17
João Pessoa	7.10	1.16	1.09	1.04	0.99	1.06	1.04	1.12	0.99	1.01	1.08	1.09	1.14
Recife	8.02	1.06	1.08	1.05	1.08	1.08	1.09	1.13	0.99	1.05	1.06	1.05	1.10
Petrolina	9.38	0.90	0.90	0.79	0.88	0.87	0.91	0.90	0.87	0.86	0.88	0.90	0.89
Maceió	9.67	1.02	1.05	0.99	0.99	1.07	1.14	0.92	0.82	0.93	1.05	0.96	1.06
Salvador	12.95	1.02	1.09	0.94	1.06	1.10	1.13	1.05	0.99	1.02	1.08	1.03	1.03
Caetité	14.07	0.84	1.06	0.90	0.94	0.96	0.86	0.96	0.88	0.93	1.03	0.90	0.91
Ilhéus	14.78	1.08	1.12	0.99	1.10	1.10	1.02	1.02	1.00	0.92	1.07	1.02	1.05

* R_{t1} - Estimated global solar radiation using Eq. 1

R_{t0} - Observed global solar radiation

while it is opposite with eq. 2 in some cases. One possible reason for this type of pattern with eq. 3 may be the temperature present underestimates in the case of Brazil - as the climate in the Stevenson's screen is considerably different compared to other parts of the world - particularity India where eq. 3 was tested initially.

It is seen, from Table 5, that percent occasions of deviations are $<$ 5% for the three models is less than 30% upto 10%, eq. 1 presents about 60% occasions while the other two models present < 40% of occasions. That means, even with eq. 1 the percent occasions of deviations > 10% are about 40%, which is considerably large.

Before, attempting to correct eqs. 1 to 3 as the necessary input data for these equations are available at only few locations. A simple regression equation similar to that employed by Reddy & Amorim (1984) for the estimation of potential evapotranspiration and/or open pan evapo-evaporation over northeast Brazil which uses rainfall as input is presented below.

Simple method-suggested

A simple equation that relates global solar radiation with precipitation and latitude is tried. This is given as:

$$R_{t4} = a + b_1\,(la) + b_2\,(P^{1/3}) \qquad (4)$$

where: R_{t4} = global solar radiation estimated using eq. 4, cal/cm²/day

la = latitude, degress

P = precipitation, mm

a, b_1 & b_2 = constants

In order to solve eq. 4, the data set of 15 locations used in the testing of eqs. 1 to 3 are used. Table 6 presents the regression parameters a, b_1 & b_2 along with R^2 (Square of correlation coefficient). R^2 is very low in few months.

Table 7 presents the ratios of R_{t4}/R_{t0} for the 15 locations. The average ratios for each of the 12 months are more or less 1.0, suggesting that estimates are very close to the observed values compared to those obtained with eqs. 1. to 3. It can be clearly seen from Table 5 that the percent occasions of deviation are $<$ 5% are more than 50% and $<$ 10% in more than 80% occasions. The majority of the deviations > 10% are mainly confined to two locations namely Petrolina & Maceió.

It appears that low ratios at Petrolina are mainly attributed to instrumental differences[5]. See for example Fig. 2, a comparison between Petrolina (9°23' S; 48°30' W, 372 m) and two nearby locations, namely Bebedouro (9°09' S; 48°22' W, 366 m) and Mandacaru (9°24' S; 40°26' W; 375 m). The measured global solar radiation at both Bebedouro and Mandacaru are considerably lower than those recorded at Petrolina, where the ratios of global solar radiation at Bebedouro or Mandacaru to Petrolina present about 87%. The comparison between observed ratios to estimated ratios suggests that both present a similar pattern except that the observed ratios are less than 10% to estimated ratios. That is, in Summer months the radiation is lower at Bebedouro and

[5] This is also seen from Table 2 (eq. 1).

TABLE 3. Ratios of global solar radiation estimated using model 2 to observed at 15 locations over northeast Brazil.

Station	Latitude (degrees)	Type ≠	R_{t2}/R_{t0}*											
			Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Turiaçu	1.72	1	1.71	1.28	1.44	1.29	1.20	1.19	1.25	1.33	1.42	1.46	1.35	1.55
		2	1.74	1.30	1.45	1.29	1.20	1.18	1.24	1.33	1.42	1.47	1.37	1.59
São Luiz	2.53	1	1.67	1.52	1.45	1.40	1.43	1.41	1.46	1.56	1.64	1.58	1.56	1.73
		2	1.70	1.54	1.46	1.40	1.43	1.40	1.45	1.56	1.64	1.59	1.58	1.77
Sobral	3.70	1	1.68	1.37	1.29	1.10	1.14	1.20	1.31	1.27	1.25	1.34	1.39	1.56
		2	1.72	1.41	1.30	1.10	1.14	1.19	1.30	1.26	1.25	1.36	1.42	1.60
Fortaleza	3.77	1	1.49	1.40	1.41	1.46	1.06	1.36	1.38	1.36	1.32	1.43	1.40	1.37
		2	1.53	144	1.42	1.46	1.05	1.34	1.36	1.34	1.32	1.46	1.43	1.41
Terezina	5.08	1	1.57	1.31	1.18	1.07	1.12	1.12	1.25	1.30	1.33	1.40	1.47	1.49
		2	1.60	1.34	1.19	1.07	1.11	1.10	1.23	1.29	1.33	1.43	1.51	1.54
Quixeramobim	5.20	1	1.79	1.57	1.39	1.24	0.98	1.29	1.46	1.46	1.43	1.53	1.62	1.76
		2	1.83	1.60	1.41	1.24	0.97	1.27	1.44	1.45	1.43	1.55	1.66	1.82
Barra do Corda	5.50	1	1.44	1.30	1.25	1.15	1.16	1.16	1.25	1.32	1.34	1.40	1.41	1.45
		2	1.48	1.33	1.26	1.15	1.15	1.15	1.23	1.31	1.34	1.43	1.45	1.50
Iguatu	6.37	1	1.57	1.49	1.30	1.11	1.20	1.21	1.39	1.35	1.36	1.46	1.62	1.82
		2	1.62	1.53	1.31	1.11	1.18	1.18	1.36	1.34	1.36	1.48	1.68	1.90
João Pessoa	7.10	1	1.21	1.12	1.09	1.01	1.02	0.99	1.05	0.98	1.05	1.16	1.14	1.20
		2	1.25	1.15	1.10	1.00	.99	.96	1.02	.97	1.05	1.19	1.18	1.26
Recife	8.02	1	1.08	1.09	1.08	1.08	1.02	1.02	1.06	0.98	1.08	1.12	1.07	1.11
		2	1.14	1.12	1.09	1.06	0.99	0.98	1.02	0.97	1.08	1.15	1.12	1.18
Petrolina	9.38	1	1.21	1.16	1.04	1.01	1.00	1.03	1.08	1.01	1.05	1.09	1.14	1.13
		2	1.27	1.20	1.05	0.99	0.97	0.99	1.04	0.99	1.05	1.11	1.20	1.20
Maceió	9.67	1	1.02	1.07	1.01	0.99	10.4	1.10	0.88	0.84	0.98	1.10	0.96	1.06
		2	1.07	1.10	1.02	0.97	1.01	1.05	0.85	0.82	0.98	1.12	1.01	1.12
Salvador	12.95	1	0.95	1.02	0.91	1.01	1.05	1.07	1.00	0.98	1.03	1.06	0.94	0.95
		2	1.01	1.06	0.95	0.99	1.01	1.01	0.95	1.96	1.03	1.09	1.00	1.02
Caetité	14.07	1	0.93	1.14	1.01	0.96	0.97	0.85	0.98	0.89	1.01	1.03	0.96	0.96
		2	1.00	1.18	1.03	0.95	0.92	0.79	0.93	0.86	1.01	1.07	1.02	1.04
Ilhéus	14.78	1	0.93	1.00	0.89	0.90	1.03	0.92	0.92	0.93	0.89	0.99	0.88	0.88
		2	1.00	1.00	0.91	0.89	0.98	0.85	0.86	0.90	0.89	1.03	0.94	0.96

* R_{t2} - Estimated global solar radiation using Eq. 2

R_{t0} - Observed global solar radiation

≠1 - According Reddy (1971) model

2 - According to Reddy (1981) modified model (K = K x N/12)

TABLE 4. Ratios of global solar radiation estimated using Eq. 3 to observed at 14 locations over northeast Brazil.

Station	Latitude (degrees)	R_{t3}/R_{t0}*											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Turiaçu	1.72	1.01	0.90	1.20	1.19	1.23	1.23	1.26	1.20	1.08	1.00	0.89	0.86
São Luiz	2.53	0.98	1.08	1.17	1.24	1.41	1.34	1.34	1.33	1.19	1.07	1.01	1.00
Sobral	3.70	0.91	0.87	0.87	1.02	1.13	1.22	1.25	1.20	1.10	1.04	0.96	0.89
Fortaleza	3.77	0.86	0.91	1.13	1.20	0.97	1.22	1.24	1.13	1.03	0.98	0.92	0.88
Terezina	5.08	0.90	0.90	0.95	1.00	1.07	1.06	1.10	1.11	1.10	1.07	1.01	0.91
Quixeramobim	5.20	0.87	0.88	0.94	1.03	0.92	1.26	1.28	1.23	1.14	1.06	1.00	0.90
Barra do Corda	5.50	0.92	0.91	0.99	1.07	1.13	1.12	1.12	1.22	1.29	1.28	1.14	0.99
Iguatu	6.37	0.84	0.95	0.97	1.00	1.14	1.20	1.30	1.24	1.15	1.12	1.09	1.02
João Pessoa	7.10	0.75	0.73	0.83	0.88	1.10	1.19	1.28	1.10	1.00	0.94	0.85	0.80
Recife	8.02	0.69	0.74	0.85	0.96	1.12	1.24	1.32	1.14	1.03	0.92	0.84	0.75
Petrolina	9.38	--	--	--	--	--	--	--	--	--	--	--	--
Maceió	9.67	0.68	0.70	0.78	0.87	1.16	1.34	1.10	0.97	0.94	0.92	0.74	0.71
Salvador	12.95	0.67	0.74	0.78	0.98	1.25	1.33	1.29	1.17	1.09	1.09	0.89	0.75
Caetité	14.07	0.67	0.84	0.85	0.98	1.09	1.02	1.15	1.03	1.05	1.16	1.03	0.86
Ilhéus	14.78	0.71	0.76	0.82	1.03	1.17	1.16	1.22	1.14	0.98	1.02	0.92	0.77

* R_{t3} - Estimated global solar radiation using Eq. 3

R_{t0} - Observed global solar radiation

TABLE 5. Percent occasions of deviations under different minimum specified limits using different models.

Model	Percent occasions of deviations (D*) in the limits				Reference
	≤ 5	5 - 10	≥ 10 - 20	≥ 20	
Eq. 1	28.3	31.7	32.8	7.2	Table 2
Eq. 2	22.8	12.8	16.6	47.8	Table 3
Eq. 3	20.8	14.9	33.3	31.0	Table 4
Eq. 4	60.0	21.7	17.8	0.6	Table 7
Eq. 4	51.3	24.2	18.3	6.2	Table 8
Eq. 4	54.7	23.2	18.1	4.0	Table 7 & 8

* $D = \frac{R_{tc} - R_{t0}}{R_{t0}} \times 100, \%$, Where R_{tc} = computed

R_{to} = observed

$D \leq 5\%$, $5\% < D < 10\%$, $10\% \leq D < 20\%$, $D \geq 20\%$.

Mandacaru compared to Petrolina (both in the case of observed and estimated values) and observed ratios are less by about 10% over the estimated values. Therefore, the radiation at Petrolina presents an overestimate by about 10% compared to Bebedouro and Mandacaru.

Apparently it is clear that either the recording at Petrolina present overestimates, or the recordings at Bebedouro and Mandacaru present underestimates. However, the 10% of higher radiation is reflected in Table 7 as an underestimation by eq. 4 - - if Petrolina data is correct, it may necessitate a 10% correction to all stations as a correction to instrumental differences.

In the case of Maceió, the observed data present an average of three years only.

In the case of São Luiz, the estimates in almost all methods present relatively an overestimate systematically.

This may probably be because the observed data present an underestimate.

Eq. 4 is also tested using independent data set for 23 locations over northeast Brazil and the ratios (R_{t4}/R_{t0}) are presented in Table 8. The pattern is similar to that of Table 7. Table 5 also presents the percent occasions of deviation in different ranges for these 23 locations and for total 38 locations. In about 78% of occasions, the deviations are less than 10%. The seven locations that contributed significantly to large deviations are Petrolina, Maceió, Acaraú, Macau, São Gonçalo, Carolina, Monte Santo, At

TABLE 6. Regression parameters and their significance.

Months	Regression parameters a	b_1	b_2	R^2
January	532	15.17	-40.80	0.92
February	608	8.50	-44.44	0.76
March	685	3.70	-44.80	0.92
April	551	0.50	-23.70	0.54
May	477	- 1.50	-16.91	0.51
June	442	- 2.00	-14.00	0.73
July	444	- 2.00	-12.07	0.61
August	501	- 1.00	-13.20	0.16
September	523	0.70	-15.000	0.06
October	517	4.70	-20.20	0.34
November	543	10.66	-35.79	0.39
December	510	10.59	-30.07	0.52

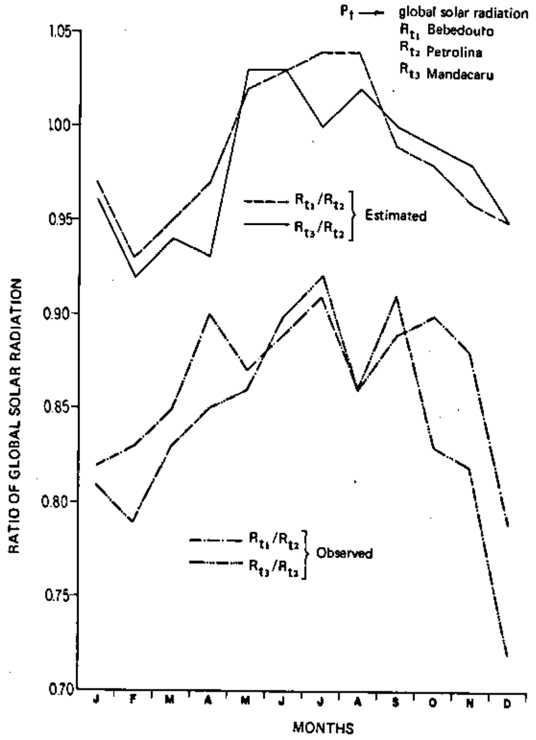

FIG. 2. Comparison of ratio of global solar radiation recorded at Bebedouro, Mandacaru to Petrolina (observed and estimated).

TABLE 7. Ratios of global solar radiation estimated using Eq. 4 to observed at 15 locations over northeast Brazil.

Station	Latitude (degrees)	R_{t4}/R_{t0}* Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Turiaçu	1.72	0.99	0.84	1.05	1.06	0.97	0.91	0.93	0.95	0.97	0.96	0.89	0.90
São Luiz	2.53	0.99	1.02	1.05	1.11	1.10	1.00	1.00	1.08	0.09	0.06	0.04	1.10
Sobral	3.70	1.03	0.93	1.02	0.98	0.96	0.97	0.97	0.99	0.96	0.97	1.03	1.00
Fortaleza	3.77	1.00	0.98	1.12	1.13	1.03	1.01	1.00	0.98	0.94	0.97	1.00	0.95
Terezina	5.08	1.00	0.91	0.98	1.05	1.01	0.90	0.89	0.92	0.96	0.96	0.95	0.95
Quixeramobim	5.20	1.07	1.03	1.02	1.01	0.98	1.01	1.01	1.01	1.02	1.03	0.09	0.06
Barra do Corda	5.50	1.01	1.02	1.08	1.09	1.04	0.97	0.96	1.08	1.14	1.17	1.11	1.07
Iguatu	6.37	0.99	1.04	1.03	0.97	0.98	0.96	1.02	1.01	1.00	1.01	1.11	1.13
João Pessoa	7.10	1.02	0.94	0.95	0.88	0.90	0.89	1.00	0.96	0.94	0.96	0.97	1.00
Recife	8.02	0.97	0.94	0.95	0.95	0.92	0.95	1.03	0.96	0.96	0.92	0.96	0.94
Petrolina	9.38	0.90	0.91	0.92	0.95	0.90	0.92	0.92	0.89	0.90	0.87	0.87	0.80
Maceió	9.67	0.93	0.97	0.95	0.88	0.94	1.03	0.85	0.82	0.88	0.93	0.88	0.94
Salvador	12.95	1.03	1.06	0.95	0.98	1.05	1.06	1.02	1.03	1.05	1.05	0.99	0.99
Caetité	14.07	0.95	1.11	1.02	1.06	1.05	0.90	0.99	0.92	0.97	1.10	1.03	1.01
Ilhéus	14.78	1.07	1.01	0.94	1.04	1.05	0.94	0.99	1.02	0.94	1.05	1.03	1.01

* R_{t4} - Estimated global solar radiation using Eq. 4 R_{t0} - Observed global solar radiation

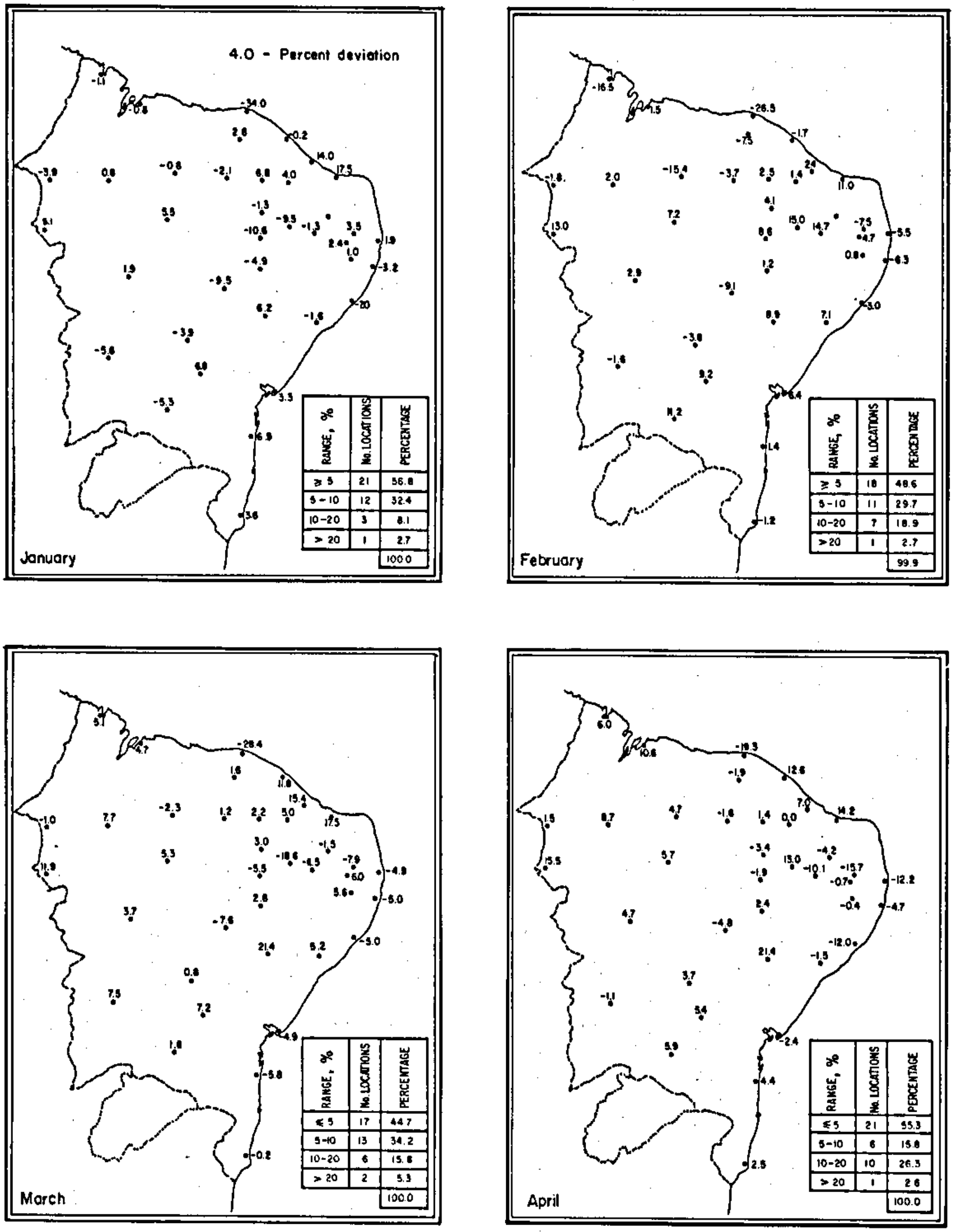

FIG. 3. Percent deviation of estimated global solar radiation from observed values.

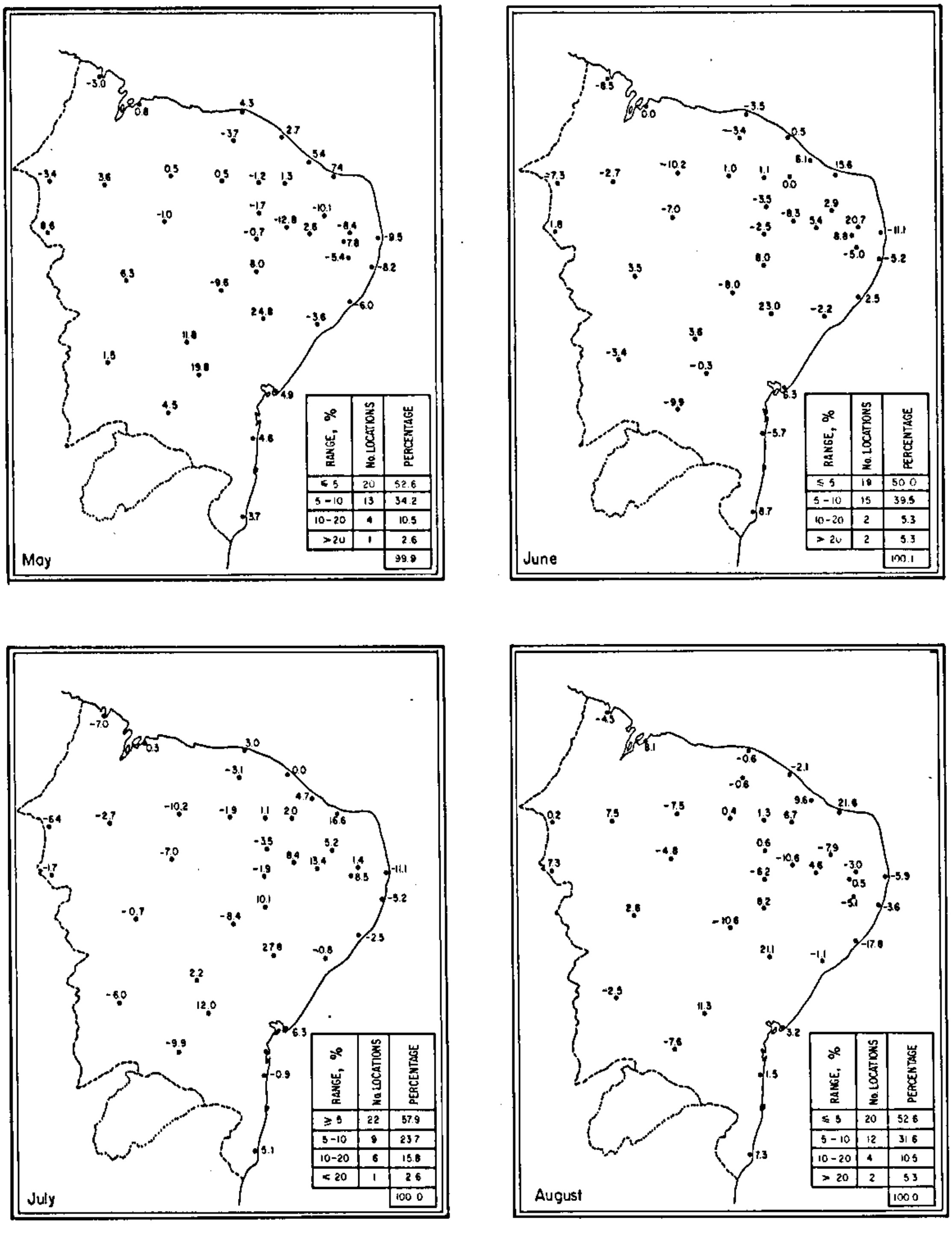

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FIG. 3. (Continuation) Percent deviation of estimated global solar radiation from observed values.

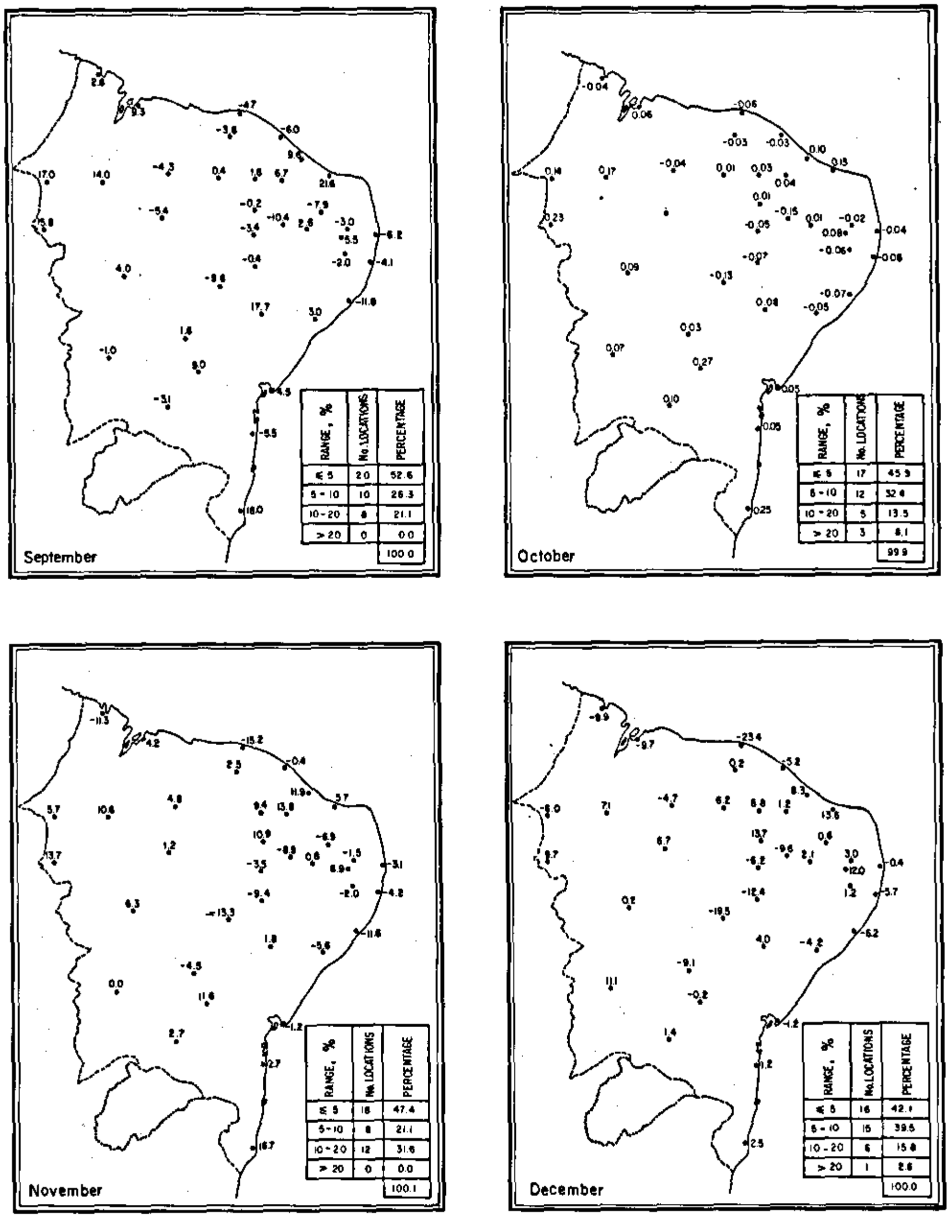

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FIG. 3. (Continuation) Percent deviation of estimated global solar radiation from observed values.

Monte Santo, the deviations are large (overestimate) during Winter, while at Acaraú they are large in Summer. Carolina and São Gonçalo present underestimates similar to Petrolina while Macau presents overestimates. These large systematic deviations may probably be due to instrumental differences (?). Fig. 3 presents these deviations ($R_{t4} - R_{t0}$) for January to December.

Table 9 presents the percent occasions of deviations in different ranges for January to December. Except in October to December the deviations are ≤ 5% in more than 50% occasions. The deviations exceed 10% in more than 30% in October while they are less than 20% in March to May and September to December. R^2 values are not truely reflecting these deviations. See for example - January and August where $R^2 = 0.92$ & 0.16 respectively, with similar deviations.

Therefore, in terms of these deviations, this method can reasonably be adopted to estimate global solar radiation over northeast Brasil. Following the similar procedure as explained by Reddy & Amorim (1984), this can be extended to estimate global solar radiation at weekly intervals.

Fig. 4 presents the spatial distribution of estimated global solar radiation over northeast Brasil for January to December (based on 38 locations data only). These figures indicate that the systematic movement of the high radiation belt with the movement of the sun and belts of high relative humidity. See for example, in Winter (May - Aug) when the sun is in the northern hemisphere, the high radiation belt is confined to drier part with low relative humidity. High radiation belt is confined to very dry northeastern parts in Summer (Sept. to Dec.) with the rainy season (Jan. to Apr.) setting over the drier parts of northeastern parts, the high radiation belt is shifted towards southeastern parts as the commencement of rains show a west to east delay (December to March/ April). These patterns also suggest that the estimates using eq. 4 are reasonably valid.

TABLE 8. Verification of Eq. 4 with independent data sets of 23 locations over northeast Brazil.

Station	Latitude (degrees)	R_{t4}/R_{t0}*											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Acaraú	2.88	0.66	0.73	0.72	0.88	1.04	0.96	1.03	0.99	0.95	0.94	0.85	0.77
Crateus	4.19	0.98	0.97	1.01	0.98	1.01	1.01	0.98	1.00	1.00	1.01	1.00	1.06
Jaguaruana	4.83	1.14	1.02	1.15	1.07	1.05	1.06	1.05	1.10	1.08	1.10	1.12	1.08
Morada Nova	5.10	1.04	1.01	1.05	1.00	1.01	1.00	1.02	1.07	1.06	1.04	1.14	1.01
Macau	5.12	1.18	1.11	1.18	1.14	1.07	1.16	1.17	1.22	1.15	1.13	1.06	1.14
Imperatriz	5.53	0.96	0.98	0.99	1.02	0.97	0.93	0.94	1.00	1.17	1.14	1.06	0.94
Cruzeta	6.42	--	--	0.98	0.96	0.90	1.03	1.05	0.92	0.96	--	0.93	1.01
Floriano	6.77	1.06	1.07	1.05	1.06	099	0.93	0.93	0.95	0.95	0.96	1.01	1.07
São Gonçalo	6.83	0.90	0.85	0.81	0.87	0.87	0.92	0.92	0.89	0.80	0.85	0.91	0.90
Areia	6.97	1.04	0.92	0.92	0.84	0.92	1.03	0.99	0.97	0.95	0.98	0.98	1.03
Patos	7.02	0.99	0.85	0.88	0.80	1.03	1.05	1.13	1.05	1.03	1.01	1.01	1.02
Campina Grande	7.22	1.02	1.05	1.06	0.99	1.08	1.09	1.09	1.01	1.06	1.08	1.09	1.12
Barbalha	7.29	0.89	0.91	0.94	0.98	0.99	0.97	0.98	0.94	0.97	0.95	0.96	0.94
Carolina	7.33	1.05	1.13	1.12	1.16	1.09	1.02	0.98	1.07	1.16	1.23	1.14	1.10
Surubim	7.72	1.01	1.01	1.06	1.00	0.95	0.95	1.01	0.95	0.98	0.94	0.98	1.01
Cabrobó	8.50	0.95	0.99	1.03	1.02	1.08	1.08	1.10	1.00	1.00	0.93	0.91	0.88
Propria	10.22	0.98	1.07	1.05	0.98	0.96	0.98	0.99	0.99	1.03	0.95	0.94	0.96
Monte Santo	10.43	1.06	1.09	1.21	1.21	1.25	1.23	1.28	1.21	1.18	1.08	1.02	1.04
Irecê	11.30	0.96	0.96	1.01	1.04	1.12	1.04	1.02	1.04	1.02	1.03	0.95	0.91
Barreiras	12.15	0.94	0.98	1.08	0.99	1.02	0.97	0.94	0.97	0.99	1.07	1.00	1.11
Lençóis	12.57	1.07	1.09	1.07	1.05	1.20	1.00	1.12	1.11	1.09	1.27	1.12	1.00
Bom Jesus da Lapa	13.27	1.02	1.03	1.04	1.05	1.06	1.04	0.99	1.03	1.04	1.09	1.06	1.00
Caravelas	17.73	1.04	0.99	1.00	1.03	1.04	1.09	1.05	1.07	1.18	1.25	1.17	1.03

* R_{t4} - Estimated global solar radiation using Eq. 4

R_{t0} - Observed global solar radiation

TABLE 9. Percent occasions of deviations are in different ranges for different months (Based on 38 locations).

Range (%)	Percent occasions											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
< 5	64.9	54.1	55.3	57.9	57.9	57.9	63.2	57.9	55.3	50.0	47.9	44.7
5 - 10	18.9	27.0	23.7	13.2	21.1	28.9	18.4	23.7	21.1	21.1	18.4	26.3
≥ 10	16.2	18.9	21.1	28.9	21.1	13.2	18.4	18.4	23.7	35.1	28.9	28.9
R^2	.92	.76	.92	.54	.51	.73	.61	.16	.06	.34	.39	.52

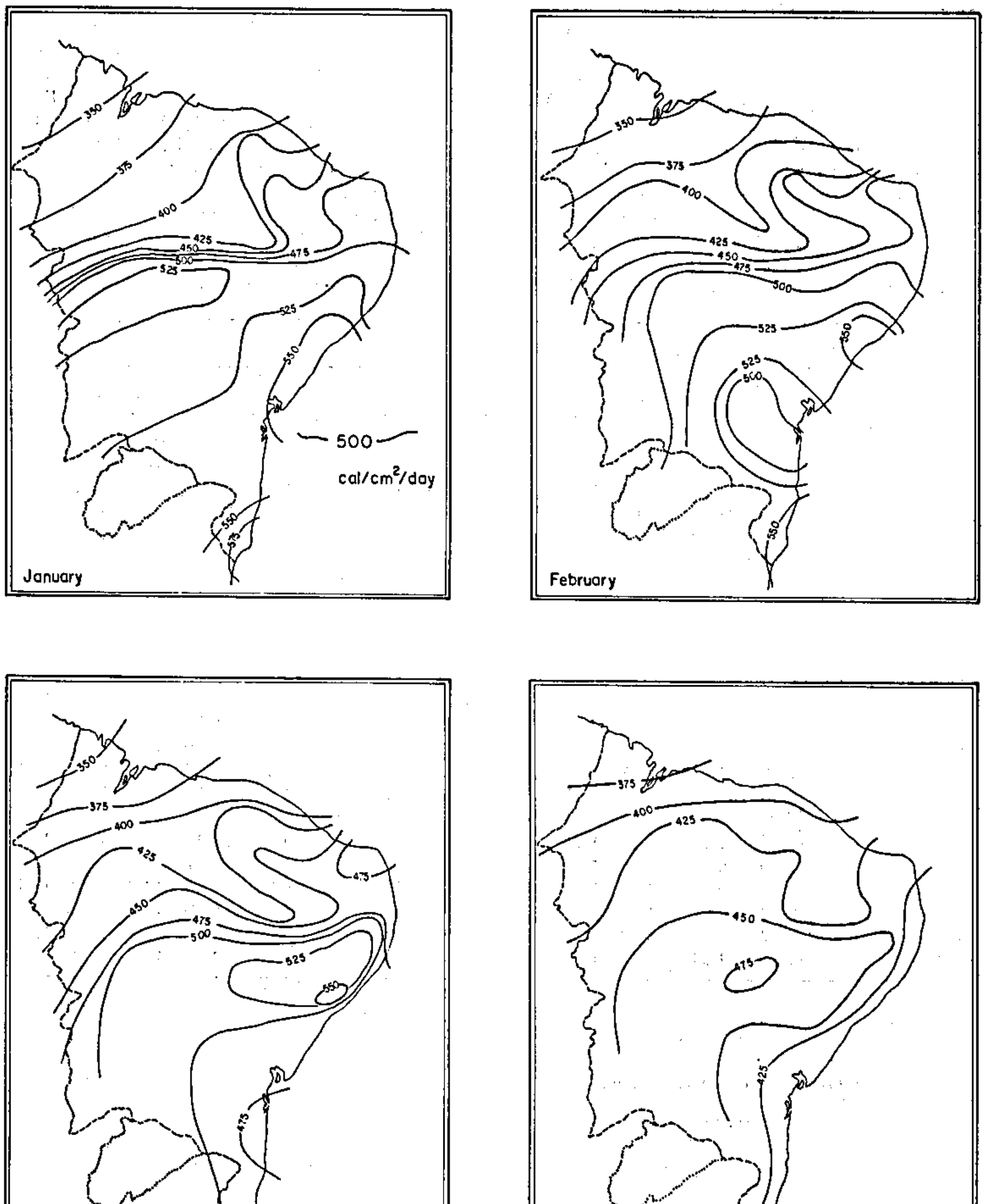
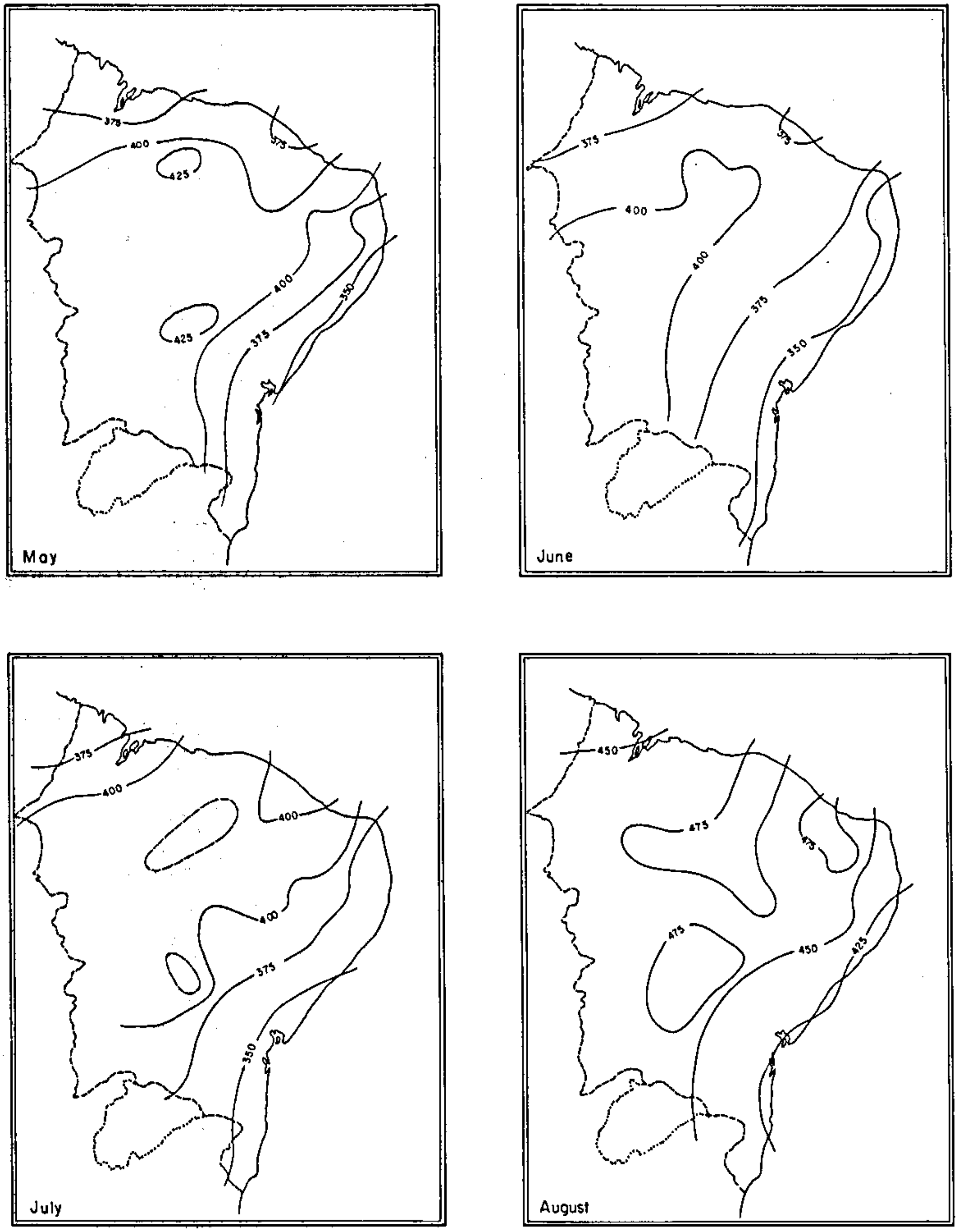
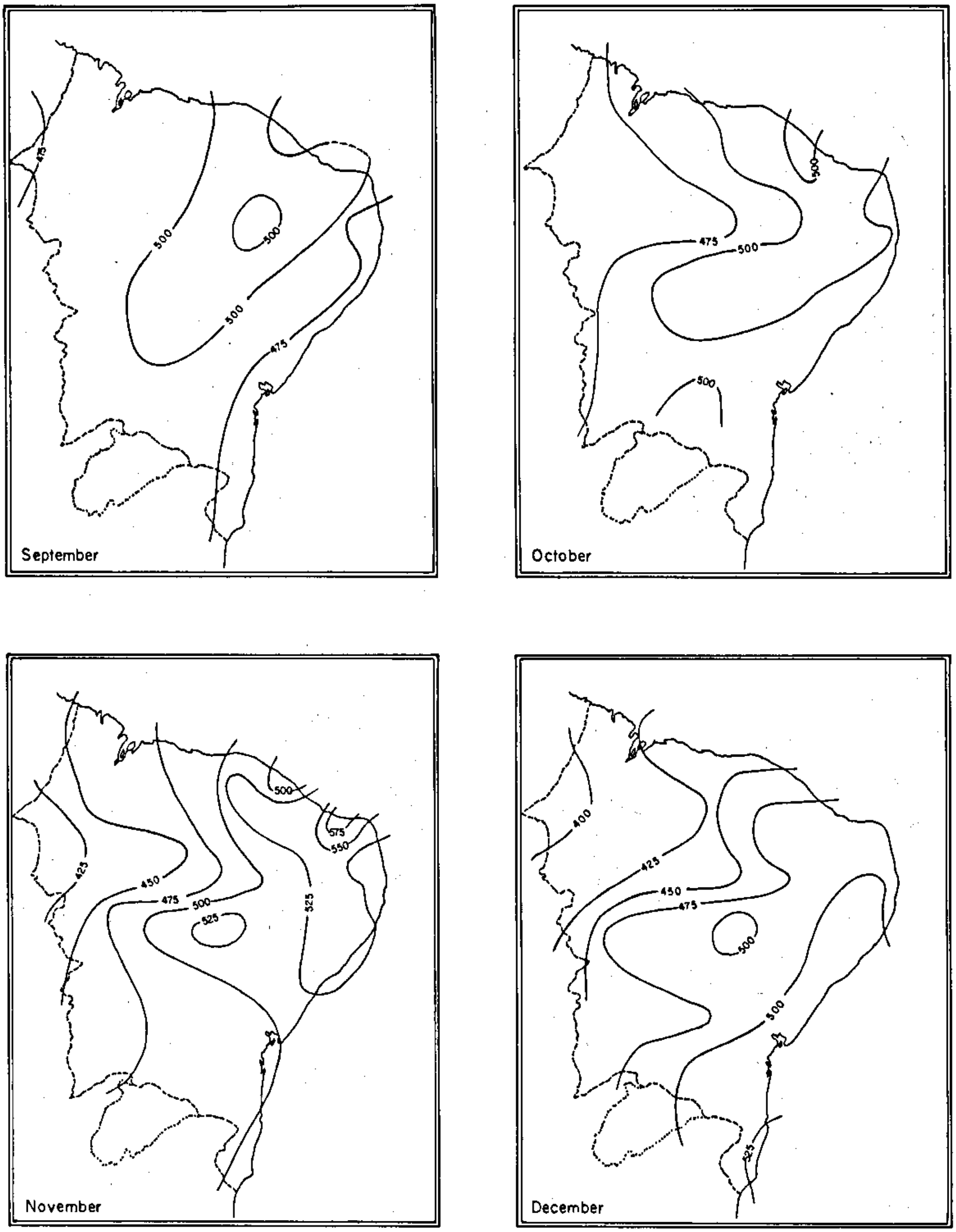


FIG. 4. Estimated global solar radiation distribution.



Continuation

FIG. 4. (Continuation). Estimated global solar radiation distribution.



Continuation

FIG. 4. (Continuation). Estimated global solar radiation distribution.

CONCLUSIONS

Three methods are tested for understanding their suitability for estimating global solar radiation over northeast Brazil. In all the three methods the estimated values exceed observed values by 5% in more than 70% of occasions. A simple regression equation that relates global solar radiation to precipitation and latitude is established. The deviations are $\leq$ 5% in more than 50% occasions with few exceptions. These results suggest that the agreement between observed and estimated values are superior in this model compared to other three models. Also, the input data are available at a quite large number of locations in the case of simple model while for the other three models the data are available only at few locations. This study also presents a probable differences in observed data due to instrumental differences. In view of these, it is proposed that the simple regression model can reasonably be used to estimate global solar radiation over northeast Brazil.

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