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SUNSHINE, GLOBAL RADIATION AND NET RADIATION IN BRAZIL

Frederico Luiz FUNARI

José Roberto TARIFA

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ABSTRACT

This paper characterizes the spatial and temporal distribution of the sunshine, global radiation and net radiation in Brazil as well as the regional potential in the country, regarding these climatic parameters. Monthly and annual maps of these parameters, based on measured and estimated data from 204 meteorological stations distributed throughout the Brazilian territory, and temporal-spatial diagrams, derived from south-north and west-east transects, show the trends in variation of these parameters and their relation to the various regional attributes of Brazil. These maps and diagrams contemplate both geographic aspects (vegetation, hydrography, orography, and geomorphology), and climatic elements (cloudiness and rain). Considering the absence of measured global radiation data, Angström's equation of 1924 was used, which takes into account the sunshine data. An estimate of the radiation balance (net radiation) was obtained by Linacre's equation of 1967. The maps of sunshine, global radiation and net radiation allowed the visualization of the spatial distribution of these elements. In the northern region, the sunshine is lower in areas with higher precipitation rates, such as around the Amazonas River mouth and in the Amapá State. Global radiation presents high values and little variation due to the high transmissivity of the atmosphere. Due to the uniformity of the relief and albedo, the net radiation also presents high values. In the northeast, high values of sunshine are explained by low cloudiness, especially in the semi-arid region (*Caatinga / Sertão Nordestino*). The maximum values of net radiation occur in the littoral. In the central-west region, in areas with greater amount of precipitation, the sunshine values are low. Global radiation and net radiation present similar values to those for the northern region. In southeastern Brazil, the distribution of sunshine is conditioned by factors such as relief, cloudiness and precipitation. Global radiation and net radiation are distributed more irregularly due to cloud cover, as in the case of the Rio Doce Basin, where the values are quite low. Net radiation is influenced by the albedo, which varies according to land use. In the South, all the elements exhibit orographic effects, which produces gradients from the coast towards the interior. Based on the spatial distribution of sunshine, global radiation and net radiation, Brazil's potential for solar energy can be verified as to qualitaty, quantity and consumptive use. This research also contributes to the agricultural planning regarding agroclimatic zoning, and crop forecasting; and to urban planning, in order to more adequately take into account the radiation balance concerning the ordering of vertical growth and the increase of green areas.

Keywords: Sunshine; Global Radiation; Net Radiation; Brazil.

RESUMO

INSOLAÇÃO, RADIAÇÃO SOLAR GLOBAL E RADIAÇÃO LÍQUIDA NO BRASIL. O presente trabalho teve como objetivo caracterizar a distribuição espacial e temporal da insolação, radiação solar global e radiação líquida no Brasil, bem como o potencial regional do país em relação a esses elementos climáticos. Mapas mensais e anuais, gerados a partir de dados medidos e estimados de 204 estações meteorológicas distribuídas por todo o território brasileiro, bem como diagramas temporo-espaciais, derivados de transectos escolhidos nas direções sul-norte e oeste-leste, permitiram representar as tendências das variações dos elementos climáticos estudados e sua relação com atributos regionais. Na elaboração dos mapas foram considerados aspectos geográficos (vegetação, hidrografia, orografia e geomorfologia) e climáticos (nebulosidade e chuva). Na ausência de dados de radiação solar global medidos, empregou-se a equação de ANGSTRÖM de 1924, que utiliza dados de insolação. A estimativa do balanço de radiação (radiação líquida) foi realizada a partir da fórmula estabelecida por LINACRE de 1967. Na região norte, a insolação é menor nas áreas com maiores totais de precipitação, como a foz do Rio Amazonas e o estado do Amapá. A radiação solar global apresenta valores altos e pouca variação, devido à transmissividade elevada da atmosfera. Em virtude da uniformidade do relevo e albedo, a radiação líquida apresenta também valores elevados. No Nordeste, os valores elevados de insolação são explicados pela baixa nebulosidade, principalmente no sertão. Os máximos de radiação líquida ocorrem no litoral. Na região centro-oeste, nas áreas onde ocorre maior quantidade de precipitação, os valores de insolação são baixos. A radiação global e radiação líquida apresentam quantidades semelhantes àquelas da região norte. No sudeste brasileiro, a distribuição da insolação é condicionada aos fatores relevo, nebulosidade e precipitação. A radiação global e a radiação líquida distribuem-se mais irregularmente devido também à nebulosidade, como é o caso da bacia do Rio Doce, onde os valores são mais baixos. Para a radiação líquida também deve ser considerado o albedo, que varia conforme o uso da terra. Na região sul, todos os elementos sofrem o efeito orográfico, que produz um gradiente no sentido do litoral para o interior. A partir da distribuição espacial da insolação, radiação global e radiação líquida pode-se verificar a potencialidade do Brasil quanto à energia solar, nos aspectos qualitativo, quantitativo e consuntivo. Esta pesquisa pode servir de subsídio para o planejamento agrícola, no que diz respeito ao estabelecimento do zoneamento agroclimático e previsão de safras, e para o planejamento urbano, na melhor adequação do balanço de radiação, levando em consideração a ordenação do crescimento vertical e incremento de áreas verdes.

Palavras-chave: Insolação; Radiação Solar Global; Radiação Líquida; Brasil.

1 INTRODUCTION

The energy from the Sun, which reaches the surface of the Earth, is the most important factor in the development of the physical processes that generate weather and climate.

The sunshine is a qualitative measure of the solar energy, while global radiation represents the sum of the radiation coming directly from the Sun, plus the radiation diffused by the particles and gases of the atmosphere – it is therefore a quantitative measure.

The net radiation is the balance of the radiation, which is the result of the energy exchanges in the atmosphere conditioned by the flux of radiation emitted by the Sun - predominantly in short waves – and by terrestrial radiation – long waves emitted by the Earth's surface. This balance has great importance due to its environmental use: air and soil heating, latent heat of evaporation and biological processes. In addition, the radiation balance is a fundamental parameter in the climatic organization of urban and agricultural spaces.

The urbanized areas have specific characteristics that are important for their energy and water balances: wide variety in surface roughness, and large capacity to store heat.

The adequacy of the buildings of an urban area is derived from the local energy balance. In this case, the radiation balance will help in the orientation, type, format, number of openings, material, color of the painting, aiming to design the buildings and urban spaces in order to respect the climatic parameters and maximize the internal and external comfort of these environments for the human beings.

In agricultural areas the study of the energy balance allows the determination of potential evapotranspiration, a climatic element that represents the ideal rainfall index. These indices, together with precipitation ones, are important variables of the water balance. The results of the water balance, at regional scale, are fundamental for the studies of storage of water in the soil or in reservoirs.

There are few studies about sunshine and global radiation in Brazil. SERRA (1969) studied seasonal and annual sunshine variations; RATISBONA (1976) elaborated an annual chart of sunshine hours using selected stations; and SERRA (1977) identified the regions of extreme values for the sunshine hours in Brazil. For global radiation there is only the work by NUNES et al. (1978), which presents monthly maps based on estimated data.

There is not yet any study on net radiation covering the whole of Brazil, since the few existing works are experiments at the micro and local level, developed in a short period of time.

Therefore, it is necessary to overcome the lack of knowledge of these elements in the spatial scale of the Brazilian territory. Due to its continental dimensions, coupled with the relatively high cost, there is great difficulty in installing instruments for the measures of sunshine, global radiation and net radiation.

The main objectives of this work are:

• To contribute to the knowledge of the average monthly and seasonal variations of solar radiation, global radiation and net radiation in Brazil;

• To determine the regional potential of the country regarding these climatic parameters;

• To estimate the net radiation based on a geographical methodology, with emphasis on spatial analysis of the Brazilian territory;

Due to the absence of measured global radiation data, the estimation was based on sunshine data using a method proposed by ANGSTRÖM (1924).

In Brazil there is not a network of instruments of net radiation, due to the high price of these equipments. Some researchers from universities' laboratories have usually estimated these parameters using meteorological data from stations. The most used formulation was established by BRUNT (1939) and adjusted by PENMAN (1948). In our case, it cannot be used due to the few relative humidity data.

The best solution found for this problem was to use the Linacre's equation of 1967, which is easier to apply because it does not require relative humidity data. Its accuracy is equal to or slightly higher than that of Brunt-Penman's formulation, considering the spatial and temporal scale of the study.

The most important results of this study can be summarized:

• Better knowledge of the spatial and temporal distribution of these parameters;

• Contribution to the study of the influence of geographical factors on the variation of spatial distribution of these elements;

• Evaluation of the Brazil's potential for solar energy as to qualitaty, quantity and consumptive use.

In addition, they may be applied for the following purposes:

• Urban planning: establishment of norms for the orientation of roads and streets, dimensioning and height of commercial and industrial buildings and houses for receiving the right amount of light and heat;

• Tourism feasibility studies of recreation and leisure areas, considering the Sun exposure. Preservation and introduction of green areas in the cities, with the purpose of establishing a better balance of energy of the urbanized areas;

• Agricultural planning: adequacy of cultivars to the photoperiod, agricultural zoning, management and adaptation of crops, crop forecasting, determination of potential evapotranspiration by the Penman's method (1948) and drying of cereals;

• In the field of technology: environmental heating, heating of fluids for industrial use, steam generation, window and awning window designs, water heating in homes and buildings (hotels, hospitals, clubs, schools, etc.), distillation of seawater or brine, concentrators for heat production, photocells for the production of electricity.

Our study has some limitations, mainly due to the difficulty of obtaining data, the low and irregular density of the meteorological network and the heterogeneity of the observation periods.

Some weather elements, such as air temperature, relative air humidity and global radiation, have failed and absent records in many stations.

In the case of sunshine, there is a greater amount of data, since the heliograph is an instrument of easy handling and not very difficult interpretation of its records. The more labor-intensive interpretation, requiring the use of manual or digital planimeters or readers, makes global radiation a meteorological element with few data series; in addition to the high price of the recording instrument, which restricts its use in our country.

There are practically no instruments installed for net radiation, which also occurs in other countries. The difficult maintenance of net radiometers requires researchers to take a number of special precautions which, if not adopted, could affect the quality of the measurements.

Due to the continental dimension of Brazil and the difficult accessibility of certain regions, the meteorological network does not have adequate density despite the efforts of the responsible entities.

The figure 1 presents the methodological approach and stages of the research, from literature review, data collection and selection, to spatial and temporal analyses of sunshine, global radiation and net radiation.

2 SPATIAL VARIATION OF SUNSHINE

2.1 Introduction

The sunshine is defined as the number of daily hours of brightness of solar disk. It is influenced by geographic and astronomical factors: latitude and inclination of the Earth's axis of rotation to the ecliptic.

For practical purposes of study, the sunshine can be distinguished in three aspects:

• Theoretical or maximum possible (N) sunshine, which depends on astronomical factors and can be calculated by trigonometric formulas that provide the duration of the day;

• Actual or effective sunshine (n), which is recorded, being a function of cloudiness;

• Relative sunshine or percentage of sunshine ($\frac{n}{N}$) is the ratio between the actual and the theoretical sunshine.

There are few studies about insolation at country-scale. SERRA (1969), in its Climatological Atlas, presented five maps: one corresponds to the total annual, and the others are representative of the seasons (January, April, July and October). RATISBONA (1976) elaborated an annual chart of sunshine hours based on twenty selected stations. Focusing on the Brazilian climate, SERRA (1977) presented monthly maps of maximum and minimum sunshine.

At the regional scale, there are two works: AZEVEDO et al. (1981) developed monthly sunshine maps using 86 stations from the northeast region; and ORSELLI (1982) studied, month by month, the sunshine for the Santa Catarina State. At the local scale, there are several studies that estimate global radiation using relative sunshine ($\frac{n}{N}$): GARCIA OCCHIPINTI (1959), CERVELLINI et al. (1966), OMETTO (1968), TARIFA (1972), SÁ (1973), MORAES et al. (1977), TUBELIS et al. (1977), BUTLER & MIRANDA (1977), and MOTA (1977).

2.2 Methodology

2.2.1 Data

The actual sunshine (n) is obtained from the reading of the burn marks made by solar rays into the diagrams (tapes) of the Campbell-Stokes sunshine recorder.

This instrument consists essentially of a glass sphere – about 10 cm in diameter – concentrically mounted on a section of a spherical arc, allowing

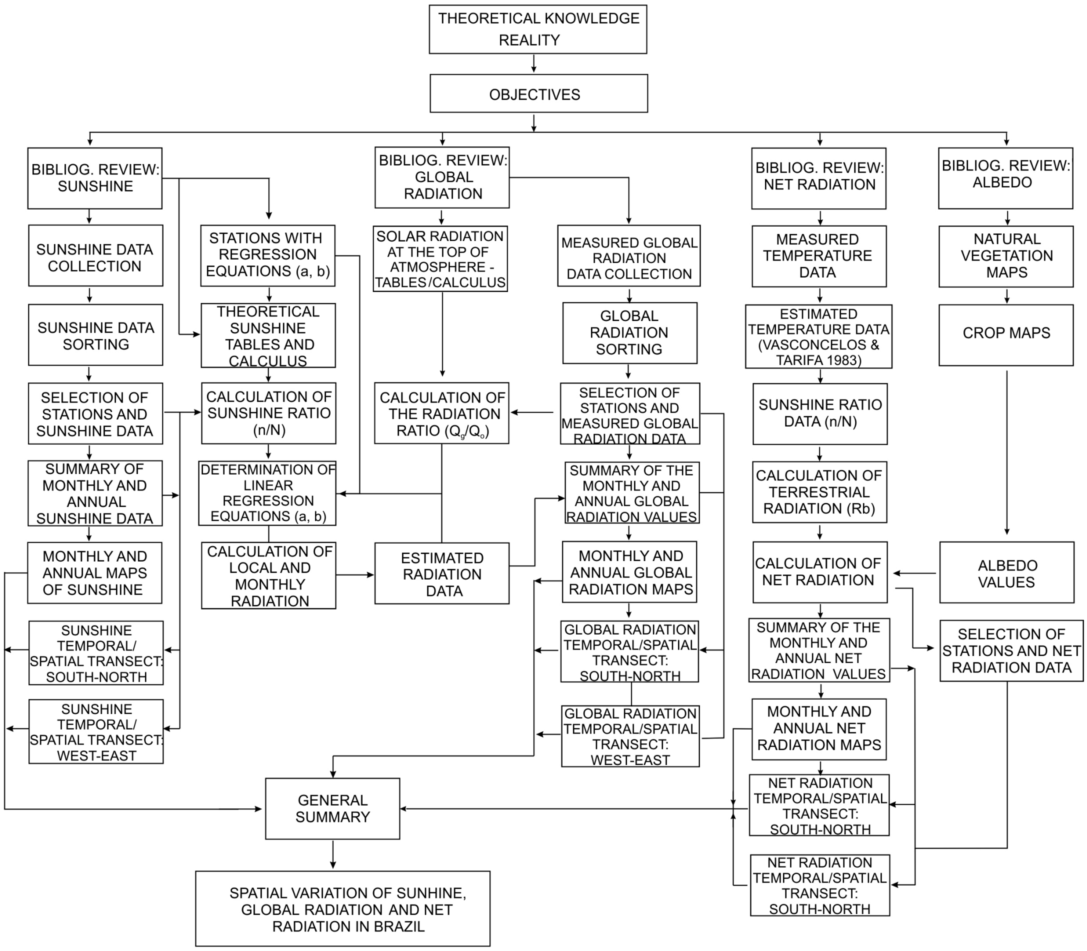

FIGURE 1 – Methodological approach.

that the sun's rays focus on the diagram. The sphere support has an adjustment system for latitude.

When installing the instrument, it is necessary to take into account that it is well oriented in azimuth and level and free horizon in 360º.

The diagrams for sunshine recording must be of good quality and printed in shade-blue color, which absorbs solar radiation. There are three sizes of diagrams, which are used according to the season: long curved (summer), short curved (winter) and straight (spring and autumn). The records should be done with an accuracy of 0.1 hour (6 minutes).

In Brazil, the main data repository is the Instituto Nacional de Meteorologia (INMET), which has a network of stations that covers practically all the national territory. There are also networks of stations and isolated stations, which belong to state agencies and universities. In this work all available data (Table 1) were used due to the low density of the network. 47% of the stations used had the complete series of the period 1931-1960 (30 years), and 57% had more than 10 years of records. Unfortunately the series are not continuous. Non-consistent data were eliminated (34 stations of a total of 231). The location of the stations is shown in figure 2 and table 2.

TABLE 1 – Number of meteorological stations per institution.

Institution	*Number of stations*	*Percentage (%)*
INMET – MA	177	86.77
UFPb	8	3.92
DAEE – SP	5	2.45
DPV/SEA – RS	4	1.96
SUDENE	3	1.47
UNESP	2	0.98
DNOS-MI	2	0.98
USP	2	0.98
IAC – SP	1	0.49
	204	100.0

Abbreviations in table 1 (References):

INMET – Instituto Nacional de Meteorologia – Ministério Agricultura (INMET 1931-1960, 1968).

UFPb – Universidade Federal da Paraíba (VILLA NOVA & SALATI 1977).

DAEE – Departamento de Água e Energia Elétrica do Estado de São Paulo (DAEE 1970-1975).

DPV/SEA – Departamento de Produção Vegetal/ Serviço de Ecologia Agrícola – RS (DPV/SEA 1967).

SUDENE – Superintendência de Desenvolvimento do Nordeste (SUDENE 1963).

UNESP – Universidade Estadual Paulista (TARIFA 1972, TUBELIS et al. 1977).

DNOS – Departamento de Obras de Saneamento – Ministério do Interior (DNOS 1978).

USP – Universidade de São Paulo (IAG – Instituto de Astronomia, Geofísica e Ciências Atmosféricas: 1958-1977 - unpublished data, ESALQ – Escola Superior de Agricultura “Luiz de Queiroz”: OGURA & DAUD 1978).

IAC – Instituto Agronômico do Estado de São Paulo – Campinas (VILLA NOVA & SALATI 1977).

The theoretical sunshine (N) consists of the maximum possible number of daily hours of brightness solar disk. It is the amount of time between sunrise and sunset.

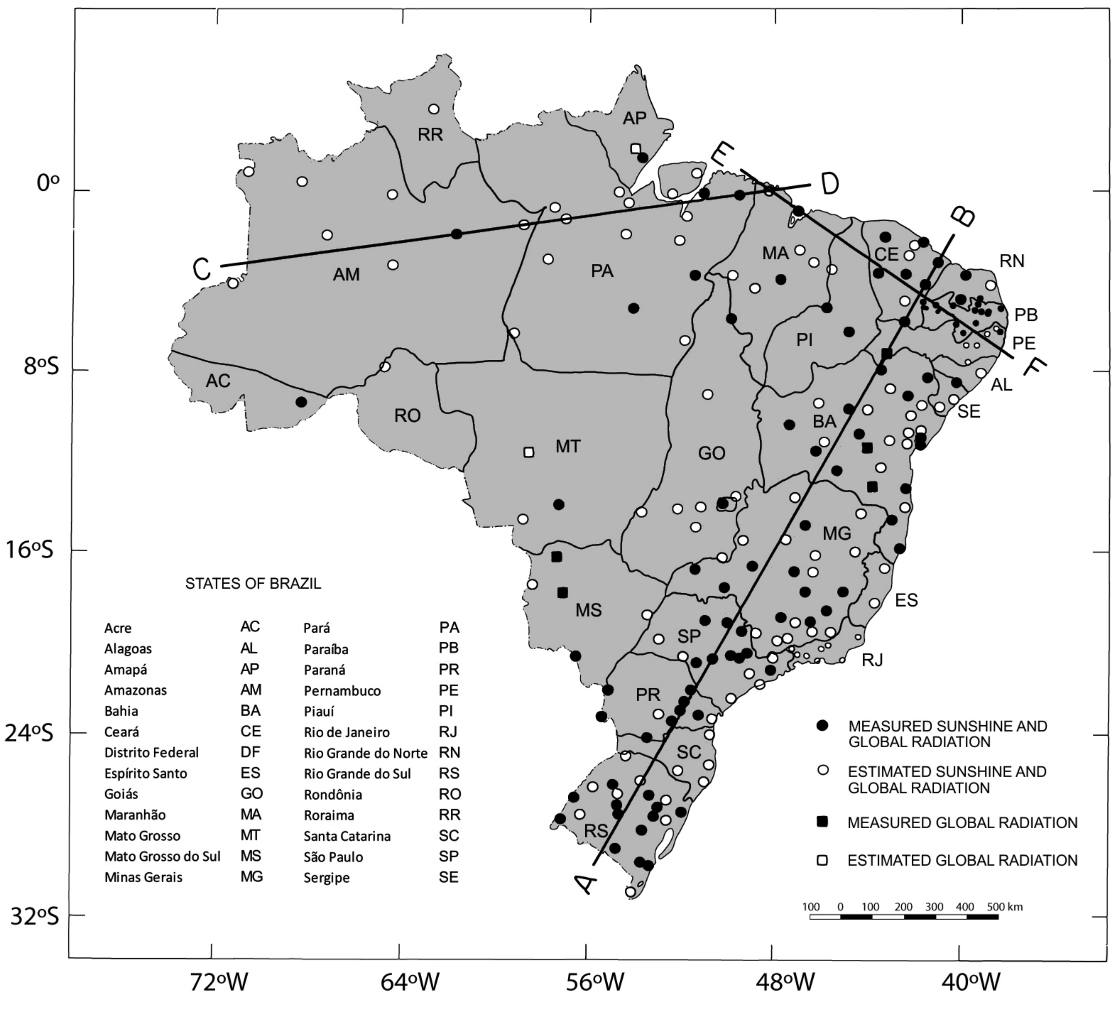

FIGURE 2 – Location of the meteorological network used in this work and the transects for the temporal-spatial analysis.

TABLE 2 – Location and identification of meteorological stations selected for the study.

Station (State)	*Latitude (° ')*	*Longitude (° ')*	*Altitude (m)*	*Number in the transect*	*Nº WMO*
Rio Branco (AC)	-9 58	-67 48	136		82915
Maceió (AL)	-9 40	-35 42	45		82994
Cupixi (AP)	0 37	-51 47	702		82093
Macapá (AP)	0 10	-51 03	9		82098
Barcelos (AM)	-0 59	-62 55	40		82113
Benjamin Constant (AM)	-4 23	-70 02	65	35	82410
Coarí (AM)	-4 05	-63 08	46	37	82425
Fonte Boa (AM)	-2 33	-66 10	56	36	82212
Iauaretê (AM)	-0 37	-69 12	122		82067
Manaus (AM)	-3 08	-60 01	60	38	82331
Parintins (AM)	-2 38	-56 44	30	39	82240
Uaupés (AM)	-0 08	-67 05	90		82106
Alagoinhas(BA)	-12 17	-38 33	131		83249
Barra (BA)	-11 05	-43 10	402		83179
Barreiras (BA)	-12 09	-45 00	439		83236
Born Jesus Lapa (BA)	-13 16	-43 25	440	23	83288
Caetité (BA)	-14 03	-42 28	882	22	83339
Canavieiras (BA)	-15 40	-38 57	4		83398
Caravelas (BA)	-17 44	-39 15	3		83498
Cipó (BA)	-11 05	-38 31	145		83192
Cruz das Almas (BA)	-12 40	-39 06	226		83222
Guaratinga (BA)	-16 34	-39 33	324		83449
Ilhéus (BA)	-14 47	-39 03	65		83348
Irecê (BA)	-11 18	-41 52	747	26	83192
Itiruçú (BA)	-13 28	-40 06	820		
Ituaçu (BA)	-13 49	-41 18	531		83292
Juazeiro (BA)	-9 25	-40 30	371	29	83411
Lençóis (BA)	-12 34	-41 23	439	25	83242
Mandacarú (BA)	-9 10	-41 10	375		
Mte .Santo (BA)	-10 26	-39 18	494		83090
Morro Chapéu (BA)	-11 13	-41 13	1002	27	83184
Paratinga (BA)	-12 41	-43 12	422	24	83238
Paulo Afonso (BA)	-9 21	-38 15	253		82986
Salvador (BA)	-13 00	-38 31	51		82224
S. Gonç. Campos (BA)	-12 26	-38 56	247		83247
Senhor Bonfim (BA)	-10 28	-40 11	558	28	82088
Serrinha (BA)	-11 39	-38 58	359		82190
Vit.Conquista (BA)	-14 57	-40 53	1042		82344
Barbalha (CE)	-7 19	-39 18	400		82784
Cratéus (CE)	-5 11	-40 40	300	51	82583
Fortaleza (CE)	-3 46	-38 33	25		82390
Guaramiranga (CE)	-4 17	-39 00	870		82487
Iguatú (CE)	-6 22	-39 18	216	53	82686
Jaguaruana (CE)	-4 50	-37 48	11	34	82493
Mondubim (CE)	-3 50	-38 34	32		422 (ant.)
Morada Nova (CE)	-6 01	-38 23	44	33	82588
Quixeramobim (CE)	-5 12	-39 18	212	52	82586
Sobral (CE)	-3 42	-40 21	83		82392
Brasília (DF)	-15 47	-47 56	1158		83377
S. Mateus (ES)	-18 42	-39 51	25		83550

Station (State)	*Latitude (° ')*	*Longitude (° ')*	*Altitude (m)*	*Number in the transect*	*Nº WMO*
Vitória (ES)	-20 19	-40 20	31		83648
Aragarças (Go)	-15 54	-52 14	345		83368
Catalão (GO)	-18 11	-47 57	857		83526
Formosa (GO)	-15 32	-47 20	912		83379
Goiânia (GO)	-16 41	-49 16	729		83423
Goiás (GO)	-15 55	-50 08	495		83374
Pirenópolis (GO)	-15 51	-48 58	740		83376
Porto Nacional (GO)	-10 31	-48 43	250		83064
Barra do Corda (MA)	-5 30	-45 16	153		82571
Carolina (MA)	-7 20	-47 28	193		82765
Caxias (MA)	-4 51	-43 20	104	49	82476
Coroatá (MA)	-4 07	-44 07	35	48	383 (ant.)
Grajaú (MA)	-5 49	-46 28	163		82568
Imperatriz (MA)	-5 34	-47 30	123		82564
São Luiz (MA)	-2 32	-44 17	51	47	82280
Turiaçu (MA)	-1 43	-45 24	44	46	82198
Cáceres (MT)	-16 03	-57 41	118		83405
Cuiabá (MT)	-15 33	-56 07	179		83361
Utiariti (MT)	-13 02	-58 14	386		83262
Corumbá (MS)	-19 05	-57 39	130		83552
Faz. Rio Negro (MS)	-19 35	-56 10	106		
Faz. S. João (MS)	-16 57	-56 20	110		
Ponta Porã (MS)	-22 32	-55 44	650		83702
Três Lagoas (MS)	-20 47	-51 42	313		83618
Barbacena (MG)	-21 15	-43 46	1170		83689
Belo Horizonte (MG)	-19 56	-43 56	850		83587
Capinópolis (MG)	-18 41	-49 34	621		83514
Caratinga (MG)	-19 48	-42 09	óĺ0		83592
Conç .Mato Dentro (MG)	-19 02	-43 26	675		83589
Diamamina (MG)	-18 15	-43 36	1290		83538
Januária (MG)	-15 26	-44 22	476	21	83386
Lavras (MG)	-21 14	-45 00	842		83687
Leopoldina(MG)	-21 32	-42 38	268		83693
Montes Claros (MG)	-16 43	-43 52	646	20	83437
Paracatú (MG)	-17 13	-46 52	711		83479
Passa Quatro (MG)	-22 23	-44 58	920		83737
Patos de Minas (MG)	-18 36	-46 31	896	18	83531
Pedra Azul (MG)	-16 00	-41 17	649		83393
Pirapora (MG)	-17 21	-44 57	505	19	83483
Poços de Caldas (MG)	-21 47	-46 33	1186		83681
Santos Dumont (MG)	-21 27	-43 33	908		83690
S.João del Rei (MG)	-21 08	-44 16	991		83688
S. Lourenço (MG)	-22 06	-45 01	900		83736
Sete Lagoas (MG)	-19 28	-44 15	732		83586
Teófilo Otoni (MG)	-17 51	-41 31	356		83492
Uberaba (MG)	-19 46	-47 56	743	17	83577
Viçosa (MG)	-20 45	-42 51	690		83642
Altamira (PA)	-3 12	-52 12	74		82353
Alto Tapajós (PA)	-7 20	-57 30	140		82741
Arumanduba (PA)	-1 32	-52 34	150	41	82183

TABLE 2 – (cont.) Location and identification of meteorological stations selected for the study.

Station (State)	*Latitude (° ')*	*Longitude (° ')*	*Altitude (m)*	*Number in the transect*	*Nº WMO*
Belém (PA)	-1 27	-48 28	5	44	82191
Breves (PA)	-1 40	-50 29	16	42	82188
Cametá (PA)	-2 15	-49 30	24	43	82263
Conç .Araguaia (PA)	-8 15	-49 17	160		82861
Itaituba (PA)	-4 16	-55 35	45		82445
Marabá (PA)	-5 21	-49 09	102		82562
Óbidos (PA)	-1 55	-55 33	37		82178
Porto Moz (PA)	-1 44	-52 14	10		82184
Santarém (PA)	-2 25	-54 20	22	40	82243
S. Felix Xingu (PA)	-6 38	-51 58	150		82669
Soure (PA)	-0 43	-48 33	10		82141
Tracuateuá (PA)	-1 05	-47 10	36	45	82194
Tucuruí (PA)	-3 43	-49 43	40		82361
Araruna (PB)	-6 32	-35 45	580		
Areia (PB)	-6 58	-35 41	624		82696
Barra Sta. Rosa (PB)	-6 43	-36 04	440		
Brejo do Cruz (PB)	-6 21	-37 30	190		
Cabaceiras (PB)	-7 30	-36 06	390	57	
Cajazeiras (PB)	-6 53	-38 12	291	32-54	
Campina Grande (PB)	-7 13	-35 53	561		82795
Esperança (PB)	-7 01	-35 52	600		
João Pessoa (PB)	-7 06	-34 52	7		82798
Mogeiro (PB)	-7 18	-35 28	100		
Monteiro (PB)	-7 53	-37 07	250	56	82792
Patos (PB)	-7 01	-37 16	249		82791
Pombal (PB)	-7 00	-38 06	200	54	445 (ant.)
Teixeira (PB)	-7 13	-37 15	770	55	
Castro (PR)	-24 47	-50 00	1009	11	83813
Curitiba (PR)	-25 20	-49 14	915		83842
Foz do Iguaçú (PR)	-25 33	-54 34	154		83826
Guaíra (PR)	-24 05	-54 15	230		83775
Guarapuava (PR)	-25 24	-51 28	1078		83834
lratí (PR)	-25 28	-50 38	837	9	83836
Jaguaríaiva (PR)	-24 15	-49 42	923	12	83814
Palmas (PR)	-26 29	-51 59	1091	8	83860
Paranaguá (PR)	-25 31	-48 31	4		83844
Ponta Grossa (PR)	-25 06	-50 10	869	10	83837
Barreiros (PE)	-8 49	-35 15	18		373 (ant.)
Bebedouro (PE)	-9 00	-40 10	350	30	
Correntes (PE)	-9 08	-36 22	374	31	806 (ant .)
Nazaré Mata (PE)	-7 44	-35 15	87		82781
Pesqueira (PE)	-8 24	-36 46	639		82892
Recife (PE)	-8 03	-34 55	7	59	82900
S. Caetano (PE)	-8 18	-36 09	551		463 (ant.)
Surubim (PE)	-7 50	-35 43	418	58	82797
Floriano (PE)	-6 46	-43 02	123		82678
Morro Cavalos (PI)	-7 51	-41 54	242		82684
Terezina (PI)	-5 05	-42 49	79	50	82578
Alto Itatiaia (RJ)	-22 25	-44 50	2199		83750
Cabo Frio (RJ)	-22 59	-42 02	7		83719
Campos (RJ)	-21 45	-41 20	11		83698
Petrópolis (RI)	-22 31	-43 11	895		83804

Station (State)	*Latitude (° ')*	*Longitude (° ')*	*Altitude (m)*	*Number in the transect*	*Nº WMO*
Pinheiral (RJ)	-22 31	-44 00	385		83754
Resende (RI)	-22 29	-44 28	439		83738
R. Janeiro (RJ)	-22 54	-43 10	31		83743
Terezópolis (RJ)	-22 27	-42 56	874		83744
Cruzeta (RN)	-6 26	-36 35	226		82693
Macau (RN)	-5 07	-36 38	6		32594
Natal (RN)	-5 46	-35 12	18		82598
Alegrete (RS)	-29 46	-55 47	121		83931
Bagé (RS)	-31 20	-54 06	216	1	83980
Caxias do Sul (RS)	-29 10	-51 12	787		83942
Cruz Alta (RS)	-28 38	-53 36	473	4	83912
Dom. Petrolini (RS)	-32 01	-52 15	5		
Encruz. do Sul (RS)	-30 33	-52 31	428		83964
Farroupilha (RS)	-29 14	-51 26	702		
Ijuí (RS)	-28 23	-53 54	498		
Iraí (RS)	-27 12	-53 14	227		83881
Julio Castilhos (RS)	-29 13	-53 41	516	3	83935
Ozório (RS)	-29 40	-50 13	38		
Passo Fundo (RS)	-28 15	-52 24	667	6	83914
Porto Alegre (RS)	-30 01	-51 13	47		83967
Rio Grande (RS)	-32 01	-52 05	2		83995
Sta. Maria (RS)	-29 42	-53 42	95	2	83936
S. Vit. Palmar (RS)	-33 31	-53 21	24		83997
S. Borja (RS)	-28 40	-56 00	96		83901
S. Luiz Gonzaga (RS)	-28 24	-55 01	260		83907
Taquari (RS)	-29 48	-51 50	76		83940
Uruguaiana (RS)	-29 45	-57 05	62		83927
Veranópolis (RS)	-28 58	-51 55	717	5	358 (ant.)
Porto Velho (RO)	-8 46	-63 55	95		82825
Boa Vista (RR)	2 49	-60 39	90		82024
Florianópolis (SC)	-27 36	-48 38	2		83897
Lages (SC)	-27 48	-50 19	937		83891
Laguna (SC)	-28 29	-48 47	31		83924
S. Fco. Sul (SC)	-26 15	-48 39	72		83874
Ataliba Leonel (SP)	-23 10	-49 20	589	13	
Botucatú (SP)	-22 56	-48 27	873	14	
Campinas (SP)	-22 53	-47 04	674		
Campos do Jordão (SP)	-22 40	-45 28	1566		
Iguape (SP)	-24 43	-47 33	3		83821
Mococa (SP)	-21 28	-47 00	665		
Mte. AIegre Sul (SP)	-22 40	-46 40	777		
Pindamonhangaba (SP)	-22 58	-45 29	570		83706
Pindorama (SP)	-21 10	-48 54	562		83664
Piracicaba(SP)	-22 48	-47 25	580	15	
Pres .Prudente (SP)	-22 07	-51 21	467		
Ribeirão Preto (SP)	-21 11	-47 43	621	16	83668
Salto Grande (SP)	-22 54	-50 00	400		
Santos (SP)	-23 56	-46 20	16		83782
S. Paulo (SP)	-23 39	-46 37	800		
Aracajú (SE)	-10 5S	-37 03	7		83096
Itabaianinha (SE)	-11 17	-37 49	208		83195
Propriá (SE)	-10 12	-36 52	34		83097

The determination of N is based on the trigonometric formulas of the astronomical triangle. This calculation requires the latitude of the place and the declination of the Sun. The latter is published in astronomical yearbooks.

There are tables that provide the times of sunrise and sunset, such as those of PEREIRA et al. (1971). To calculate the theoretical sunshine, we use these tables, applying two corrections:

a) Atmospheric refraction correction, in which the following average values were considered for Brazil: Mean temperature = 20 °C; average altitude = 400 m, which corresponds to an average atmospheric pressure of 725 mmHg (967 hPa). The value is additive: 2 · 34' = 68' (sunrise and sunset);

b) Correction due to the mean apparent diameter of the Sun. Astronomically it is considered the center of the disc of the star, at sunrise and at sunset. This disc has an average apparent diameter of 32' (ie, 16' at sunrise + 16' at sunset).

The sum of the both corrections gives the following result:

- Refraction correction: 2 · 34' = 68'
- Correction due to the diameter of the solar disk: 2 · 16' = 32'
- Total value (additive): 100'

Since one hour corresponds to 15° (= 900'), 100' is equal to 0.111 h, or approximately 6 min. This value was added to the tables of PEREIRA et al. (1971). These corrected tables are coherent with the Smithsonian Meteorological Tables (LINACRE 1969a).

We thus obtained the duration of the day-length ($\dot{N}$) for each season and each month. $\dot{N}$ of day 15 was considered representative of the month. February was considered with 28 days.

The monthly total of theoretical sunshine N was calculated by the equation:

$N = \dot{N}$ x number of days of the month

The sunshine ratio ($\frac{n}{N}$) (dimensionless) was obtained by division of the actual sunshine values (n) by the theoretical sunshine (N). This parameter is important for the estimation of global solar radiation by Angström's method (1924).

2.2.2 The cartographic treatment

Monthly charts were produced using a base map from IBGE, with a scale of 1: 5,000,000, in azimuthal conformal projection. Isocontour maps of sunshine (monthly and annual) were traced based on 197 stations data, considering the relief, natural vegetation, hydrography, geomorphology, cloudiness and rain.

Spatial-temporal diagrams (abscissa axis = meteorological stations, ordinate axis = months of the year) were generated for transects (south-north and west-east) (Figure 2). The selected stations along the transects are shown in table 2. This method, applied by SNYTKO (1978) for the study of geosystems, provides a visualization of the spatial-temporal trends of sunshine in Brazil.

2.3 Results and discussion

The spatial distribution of the sunshine can be visualized in the annual and monthly maps (Figures 3, 4) (see APPENDIX for station data and radiation budget results – available online at http://dx.doi.org/10.5935/0100-929X.20170009). It depends on several factors that are influenced by regional characteristics. The two spatial-temporal diagrams (south-north and west-east, Figure 5) provided a better understanding of the variation over time and space, and also the influence of geographical factors on the sunshine.

In the northern region of Brazil, the effects of latitude are less pronounced due to the proximity of the equator. The influence of the orography is also not evident, because of the relief has low expression. The sunshine distribution is similar to the rainfall chart. In general, the sunshine is lower where it rains more. The lower values of sunshine occur in the first half of the year, when precipitation is higher (Figures 3, 4).

In the northeast region, the sunshine values are high due to the low cloudiness. The relief in this region is responsible for these variations, mainly in the valley of the São Francisco River, where the values increases from the coast to the interior.

In the central-west region, the low orography does not play an important role in the sunshine. North of this region, the values are smaller due to the greater cloudiness and precipitation.

In the southeast region there is a strong influence of the orography; this effect is added to the existence of frontal cloudiness. The sunshine smallest values occur in the region of the Rio Doce Valley (MG/ES) and the Serra do Mar. In the latter one, precipitation reaches the maximum values in Brazil.

The relief and cloudiness are also the main factors for the sunshine variations in the south region. The cloudiness is greater in the coast of Paraná and Santa Catarina, which corresponds to the low number of hours of sunshine in this region.

The effects of the orography and cloudiness could be visualized in the spatial-temporal diagrams.

The south-north transect (Figure 5) extended from the Uruguay border to the coast of the Ceará State, and shows the following compartmentation:

• From the Uruguay border to the southern of the São Paulo State: high values from October to March, decreasing in winter;

• From the southern part of the São Paulo State to the Triângulo Mineiro (MG): there are no major variations during the months of the year; summer is the season with the lowest values;

• From the Triângulo Mineiro (MG) to the south-central of Bahia State: highest values of sunshine in winter (May to August), and lowest values in the summer;

• From the south-central area of Bahia State to the coast of Ceará State: characterized by irregularity throughout the year; the lowest values occur in the winter, which is the rainy season. The relief also produces local effects.

The west-east transect (Figure 5) extended from Benjamin Constant (AM) to Recife (PE), and shows the following compartmentation:

• From the Colômbia border to the mouth of the Juruá River: sunshine values are almost the same throughout the year;

• From the mouth of the Juruá River to the mouth of the Amazon River: the lowest values of sunshine correspond to the rainy season (December to April), while the highest ones concentrate in the rest of the year;

• From the mouth of the Amazon River to the Piauí State: the lowest values occur from February to April, whereas the highest ones occur from August to November;

• From the State of Piauí to the coast of the Pernambuco State (Recife): there is a great irregularity from place to place, due to the orography.

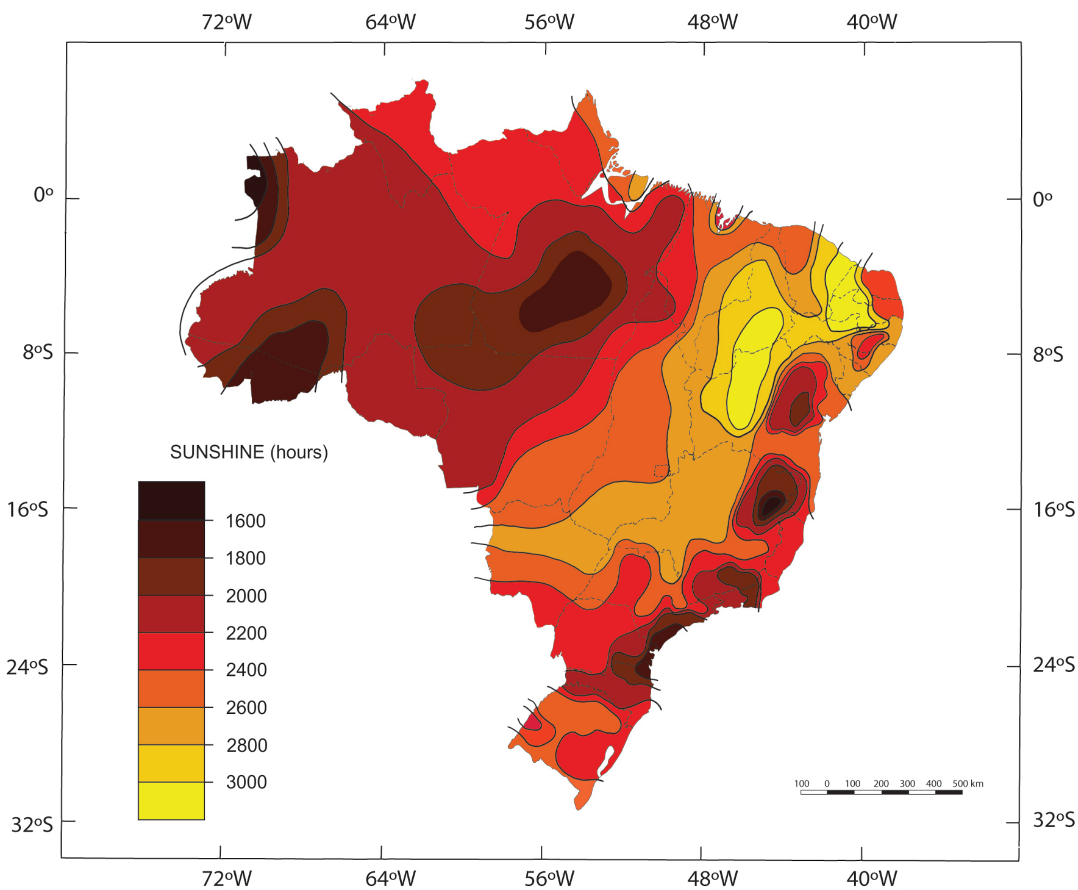

FIGURE 3 – Annual sunshine (hours) map.

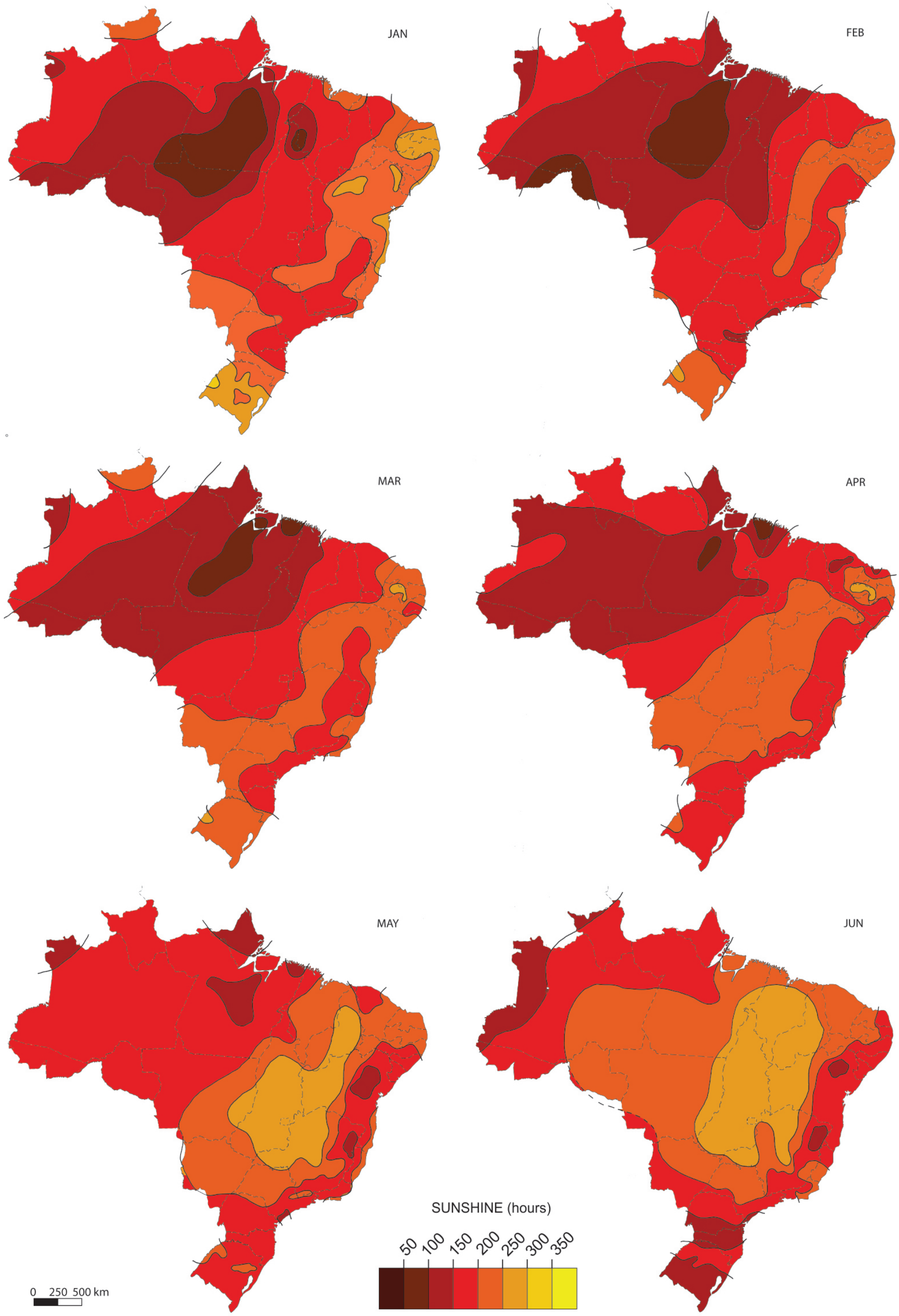

FIGURE 4 – Monthly sunshine (hours) maps (January - June).

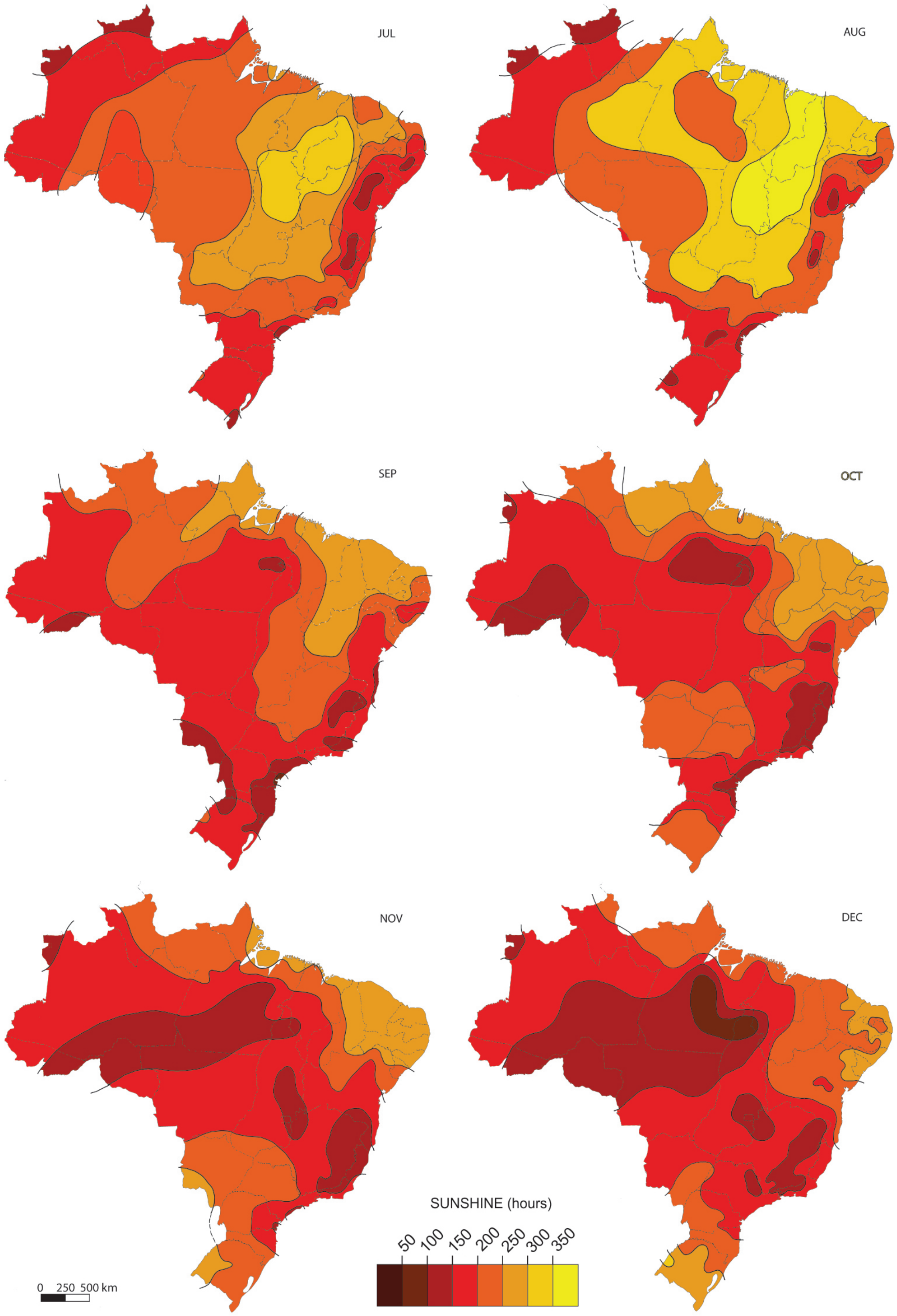

FIGURE 4 (continuation) – Monthly sunshine (hours) maps (July - December).

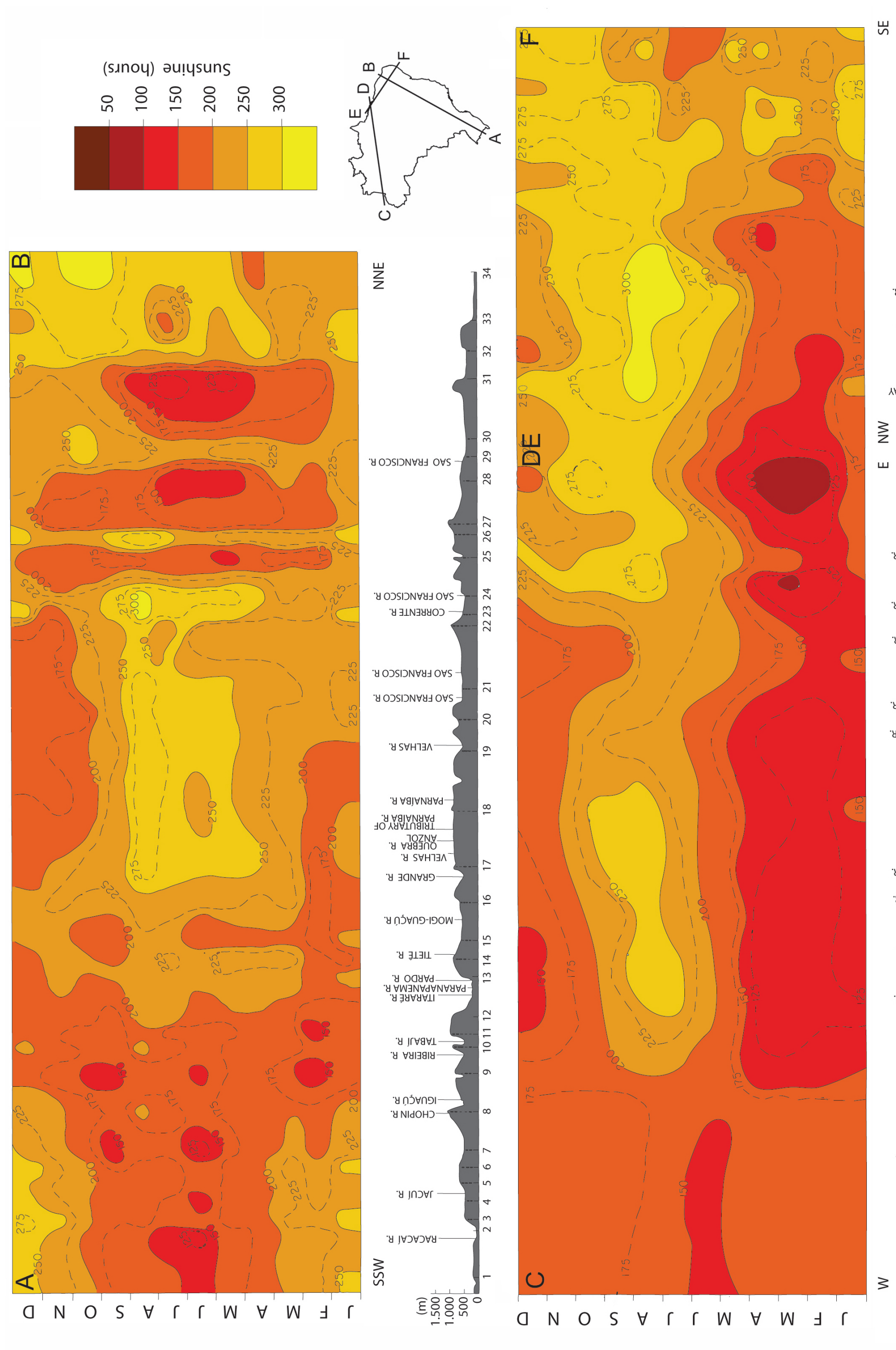

FIGURE 5 – Temporal-spatial variation of the sunshine along the south-north (A-B) and west-east (C-D and E-F) transects (Figure 2). See identification of the stations (numbers along the profile) in the table 2.

Comparing this study with the previous ones, we can observe that the monthly maps of January and April, and July and October (Figure 4), are similar to those of SERRA (1969). The main difference is that this author did not have many stations and had to interpolate lines in the monthly maps. The annual map (Figure 3) is very similar, except for some regions, due to the greater number of meteorological stations in the present study.

In general, the annual map by RATISBONA (1976) is very similar with the one of the present study, which is more detailed due to the greater number of stations.

Our monthly sunshine maps are similar to the SERRA (1977)'s maps. They agree approximately with figure 4, however, we used a greater number of stations and years of observation, and the time-space diagrams for a more accurate analysis.

At the regional scale, comparing with the maps by AZEVEDO et al. (1981) for the northeast region and ORSELLI (1982) for the Santa Catarina State, we can observe that both are more detailed due to the greater number of stations analyzed. But, in general, there is a great similarity between these maps and the present ones.

3 SPATIAL VARIATION OF GLOBAL RADIATION

3.1 Introduction

The amount of solar energy that reaches the earth's surface is called global radiation. It is composed by radiation that comes directly from the solar disk (direct radiation) and from diffuse radiation. The latter is the fraction of the extraterrestrial radiation that suffers dispersion in the atmosphere.

The radiation flux that falls perpendicularly on a unit area surface at the upper boundary of the atmosphere at the mean distance between the Sun and the Earth is called the solar constant.

The value of this constant, according to the best determinations is:

1.94 cal cm^{-2} min^{-1} or 1.94 ly, or
135.3 mW cm^{-2} (± 1.3%)

For practical purposes solar radiation can be studied in three ways:

- Extraterrestrial radiation or radiation at the top of the atmosphere (Q_o): it is the maximum possible theoretical radiation for a given day and place. Their values can be found in tables. In Brazil, they were calculated by SALATI et al. (1967);
- Global radiation measured (Q_g) or estimated at the soil level, whose data are published by the institutions responsible for the collecting;
- Radiation ratio ($\frac{Q_o}{Q_g}$), which is an index of atmospheric transmissivity. This ratio can be correlated with relative sunshine, in order to estimate global radiation.

There are few studies about global radiation at national level, and most are incomplete. In a preliminary work, MOTA et al. (1977) estimated the annual values of global radiation, using the methodology proposed by FRÈRE et al. (1975). NUNES et al. (1978) produced monthly maps of global solar radiation, based on the formulation by BENNETT (1975) for the Northern Hemisphere. VILLA NOVA & SALATI (1977) surveyed the measured data of solar radiation in Brazil, listing 97 stations.

At the regional scale, CERVELLINI et al. (1966), by studying monthly measured data of radiation and sunshine, established an equation to estimate global radiation for the whole State of São Paulo. This formula was also used by MARDEN DOS SANTOS et al. (1966) for the Rio de Janeiro State. MOTA & BEIRSDORF (1971) produced an annual map for the Rio Grande do Sul State. VILLA NOVA et al. (1977) determined the values of global radiation for the Amazon region using the equation of OMETTO (1968). OGURA & DAUD (1978) estimated the global radiation for the State of São Paulo, considering several meteorological elements (visibility, amount of atmospheric water, etc.). MACEDO et al. (1978) estimated global radiation for 15 stations in the Legal Amazon.

Due to the low cloudiness, the northeast region deserved special attention from the researchers: a team from SEPLANTEC-BA (1979) carried out a monthly mapping of global radiation in the Bahia State. CEBALLOS et al. (1983) studied the influence of the atmospheric turbidity and the precipitable water on global radiation. COSTA & FRAIDENRAICH (1981) estimated direct radiation values for the northeastern region. AZEVEDO et al. (1981) mapped the monthly global radiation values to the whole northeastern region. ORSELLI (1982) produced monthly charts of global radiation, with estimated values, for the Santa Catarina State.

At the local scale, most of the papers established the relationship between solar radiation and global solar radiation in order to determine the linear regression equations for the estimation of the radiation, when there is only sunshine data. This estimation was initially established by ANGSTRÖM (1924) and then, with some modifications, by PENMAN (1948), BLACK et al. (1954), GLOVER and McCULLOCH (1958), DAVIES (1965) and LINACRE (1969b).

At the local scale, we can cite the papers: GARCIA OCCHIPINTI (1959), OMETTO (1968), REIS et al. (1970) cited by TARIFA (1972), OMETTO & VILLA NOVA (1973), SÁ (1973), MORAES et al. (1977), TUBELIS et al. (1977), BUTLER & MIRANDA (1977), MOTA (1977), DECICO & MARDEN DOS SANTOS (1980), BORGES SIMAS (1980), FESTA (1981), and CARMO FILHO (1981).

3.2 Methodology

3.2.1 Data

For measurements of global radiation, the most used instrument is the actinograph of Robitzsch-Fuess, whose principle of operation is the differential heating of bimetallic plates. Two are painted in white and one in black. The difference in plate expansion is proportional to the differential absorption of incident solar radiation.

Actinographers have a special glass dome for the protection of sensitive elements. A mechanical system of levers transmits to a pen the variations of the radiation. The record is made on a diagram that is placed on a clockwork drum, with daily rotation. The sensitivity of this instrument is of the order of 5-10%.

Another instrument used for global radiation measurement is the Eppley Pyranometer; but its use is more restricted due to its high cost and difficult maintenance.

The pyranometer consists of a temperature-compensated thermopile, mounted inside a special glass dome. The thermopile consists of 10 to 50 thermocouple pairs of platinum-rhodium (90% - 10%), gold-palladium (60% - 40%) or silver-bismuth. Due to its accuracy (± 2%) this instrument is considered a secondary standard.

The actinograph diagrams are interpreted by integrating the area. This requires the use of planimeters, and manual or digital readers. At the end of the process is provided the daily total of global solar radiation (ly day^{-1}).

In Brazil, due to the low density of the network of stations, we used all available data from INMET and other institutions (Table 3). 46.4% of them had 5 to 18 years of data record.

The total solar radiation reaching at a horizontal surface per unit area at the top of the atmosphere (Q_o) is a function of the latitude of the place (Φ) and the declination of the Sun (δ):

$$Q_o = \left(\frac{2}{\pi}\right) \cdot \dot{N} \cdot I_o \cdot \cos(\delta - \Phi) \qquad \text{[Eq. 1]}$$

Q_o: solar radiation at the top of the atmosphere on a horizontal surface per unit area (ly day^{-1})

π: 3.1416

I_o: solar constant (1.94 ly)

δ: declination of the Sun - provided by astronomical tables or annuals (º).

Φ: location latitude (º)

$\dot{N}$ (length of day in minutes) = $[0.1333 \cdot \arccos - (\tan\delta \cdot \tan\Phi)] \cdot 60$

We applied corrections for the calculated value due to the atmospheric refraction and the diameter of the Sun. The sum of the both corrections

TABLE 3 - Meteorological stations used for the study of global radiation.

Institution	*Measured data (number of stations)*	*Estimated data (number of stations)*	*Total of stations*	*%*
INMET	77	101	178	87.1
Univ. Fed. PB	8	0	8	3.9
Serv. Ecol. Agr. RS	4	0	4	2.0
IAC – SP	4	0	4	2.0
SUDENE	2	0	2	1.0
DNOS – MI	2	0	2	1.0
DAEE – SP	0	2	2	1.0
UNESP – SP	1	1	2	1.0
USP (IAG / ESALQ)	1	1	2	1.0
Total	99	105	204	100.0

gives an additive of 0.1 h (6 min). To avoid all these calculations, we used tables generated by SALATI et al. (1967) for Brazil that provide the Q_o indexes for all the year and for the latitudes from 10º N to 40º S. The value of day 15 is taken as representative of the month.

The $\frac{Q_g}{Q_o}$ ratio (radiation ratio) indicates the percentage of energy received at the top of the atmosphere that reaches the soil surface. It represents the atmospheric transmissivity over the site of observation. The $\frac{Q_g}{Q_o}$ ratio was obtained by simple division and its result (dimensionless) was rounded to the second decimal place. When no global solar radiation data are recorded, estimates are taken from meteorological data.

The most well-known formulation was proposed by ANGSTRÖM (1924):

$$Q_g = Q_o \cdot \left(a + b \cdot \frac{n}{N} \right) \quad \text{[Eq. 2]}$$

where:

Q_g: global solar radiation at ground level (ly day^{-1})

Q_o: radiation at the top of the atmosphere (ly day^{-1})

$\frac{n}{N}$: sunshine ratio

a, b: statistical parameters of the regression line

The regression line is given by:

$Y = a + bx$

$y = \frac{Q_g}{Q_o}$ (independent variable)

$x = \frac{n}{N}$ (dependent variable)

The least squares method was used for the determination of *a* and *b*. In addition to the parameters *a* and *b*, the correlation coefficient (r) between the variables and the coefficient of determination (r^2) were obtained from a total of 65 regression lines (Table 4).

For stations without actinograph records, but with sunshine data from sunshine recorders, global radiation was estimated using the values of *a* and *b* from the nearest station or from the same or similar climate region. Vegetation, topography, altitude, etc. were still taken into account for this estimate.

3.2.2 The cartographic treatment

Monthly maps were produced using a base map from IBGE, with a scale of 1: 5,000,000, in azimuthal conformal projection. Isocontour maps of global radiation were traced based on 204 stations data, considering the relief, natural vegetation, hydrography, geomorphology, cloudiness and rain. Spatial-temporal diagrams (abscissa axis = meteorological stations, ordinate axis = months of the year) were generated for transects (south-north and west-east) (Figure 2). The selected stations along the transects are shown in table 2. This method, applied by SNYTKO (1978) for the study of geosystems, provides a visualization of the spatial-temporal trends of global radiation in Brazil.

3.3 Results and discussion

The spatial distribution of the global solar radiation can be visualized in the annual and monthly maps (Figures 6, 7) (see APPENDIX available online). The two spatial-temporal diagrams (south-north and west-east, figure 8) provided a better understanding of the variation over time and space, and also the influence of geographical factors on the global radiation. The monthly and annual spatial distribution of this parameter is conditioned by several factors and varies according to the characteristics of each region. These variations are somewhat different from those of sunshine.

The regions with the maximum values of sunshine do not coincide necessarily with those of higher global radiation. In the northern region of Brazil, the effects of latitude are less pronounced due to the proximity to equator. Although the cloudiness of this region is relatively high, the transmissivity is high. The global radiation has minimum values in the Amapá State and the Amazonas River mouth (less than 350 ly day^{-1}). In the rest of this region the values are above 400 ly day^{-1}. The minimum values are found in regions where there is higher cloudiness and lower atmospheric transmissivity.

In the northeast of Brazil, the highest values of global radiation occur in the semi-arid region (*Caatinga*), due to the low cloudiness and high transmissivity of the atmosphere.

In the central-west region, the values are similar to those of the Amazon region. The lowest values occur in the southeast of the Mato Grosso do Sul State, whereas the highest ones in the most part of the Mato Grosso State and in the region of the Mato Grosso's Pantanal wetlands.

The variations of the global radiation in the southeast region are due to the presence of

TABLE 4 – Stations with *a* and *b* values for Angström's formula.

Station	*a*	*b*	*r²*
Rio Branco - AC	0.42	0.5	0.83
Manaus - AM	0.20	0.65	0.86
Barreiras - BA	0.31	0.41	0.94
B. Jesus Lapa - BA	0.32	0.35	0.85
Caetité - BA	0.28	0.49	0.88
Caravelas - BA	0.22	0.53	0.86
Guaratinga - BA	0.25	0.5	0.86
Ilhéus - BA	0.28	0.45	0.9
lrecê - BA	0.24	0.46	0.72
Juazeiro – BA (1)	0.25	0.51	
Lençóis - BA	0.26	0.58	0.9
Monte Santo - BA	0.22	0.52	0.87
Paulo Afonso - BA	0.32	0.36	0.94
Salvador - BA	0.23	0.49	0.77
Cratéus - CE	0.24	0.5	0.91
Fortaleza - CE	0.13	0.59	0.96
Jaguaruana - CE	0.13	0.49	0.79
Brasília - DF	0.18	0.49	0.80
São Mateus - ES	0.24	0.25	0.76
Barra Corda - MA	0.31	0.28	0.94
Carolina - MA	0.22	0.39	0.96
São Luiz - MA	0.30	0.32	0.92
Cuiabá - MT	0.34	0.28	0.94
Ponta Porã - MS	0.27	0.45	0.75
Barbacena - MG	0.14	0.53	0.76
Belo Horizonte - MG	0.23	0.38	0.96
Lavras - MG	0.21	0.30	0.92
Montes Claros - MG	0.25	0.40	0.90
Sete Lagoas - MG	0.25	0.21	0.92
Viçosa - MG	0.21	0.25	0.85
Belém- PA	0.25	0.31	0.82
Marabá - PA	0.30	0.20	0.71
S. Félix Xingu - PA	0.38	0.32	0.82
Tracuateuá - PA	0.18	0.59	0.76
Barra S. Rosa - PB	0.28	0.42	0.88

(1) SÁ (1973)
(2) TUBELIS et al. (1977)

Station	*a*	*b*	*r²*
Cabaceiras - PB	0.31	0.39	0.71
Esperança - PB	0.31	0.43	0.84
João Pessoa - PB	0.33	0.32	0.82
Monteiro - PB	0.33	0.38	0.80
Pombal - PB	0.26	0.46	0.82
Foz Iguaçu - PR	0.16	0.32	0.88
Guaíra - PR	0.20	0.25	0.93
Ponta Grossa - PR	0.15	0.22	0.80
Recife - PE	0.35	0.23	0.79
Surubim - PE	0.34	0.38	0.90
Floriano - PI	0.21	0.46	0.94
Morro Cavalos - PI	0.27	0.41	0.81
Macau - RN	0.43	0.28	0.82
Bagé - RS	0.23	0.45	0.84
D. Petrolini - RS	0.15	0.76	0.91
Encz. Sul - RS	0.11	0.77	0.83
Ijuí - RS	0.12	0.80	0.78
Ozório - RS	0.02	0.92	0.81
Rio Grande - RS	0.21	0.60	0.71
Taquari - RS	0.09	0.66	0.88
Uruguaiana - RS	0.22	0.42	0.74
Atal. Leonel - SP	0.02	0.72	0.89
Botucatu – SP (2)	0.24	0.47	0.92
Campinas - SP	0.25	0.56	0.94
Est. S. Paulo (3)	0.24	0.58	
Mococa - SP	0.17	0.68	0.81
Mt. Alegre Sul - SP	0.27	0.53	0.92
Pindamonhangaba - SP	0.26	0.55	0.93
Pindorama - SP	0.16	0.60	0.88
Piracicaba - SP	0.27	0.52	0.87
Pres. Prudente – SP (4)	0.19	0.39	0.89
Rib. Preto - SP	0.31	0.46	0.93
S. Paulo - SP	0.32	0.39	0.84
Propriá - SE	0.26	0.56	0.81

(3) CERVELLINI et al. (1966)
(4) TARIFA (1972)

cloudiness, which increases by the orographic effect of the mountain ranges. The lowest values occur in the Rio Doce Valley, where the cloudiness is persistent and strong. In addition, transmissivity is low in this part of Brazil.

In the southern region, the Paraná State and northern Santa Catarina present low global radiation (Q_g) values, due to the strong cloudiness and precipitation, besides the low transmissivity. The highest values of this region are located along the coast of these states. Due to the orography, the values decrease from the coast to the interior.

The sunshine is a function of the amount of cloudiness, whereas global radiation varies according to the amount and type of clouds, and also with transmissivity.

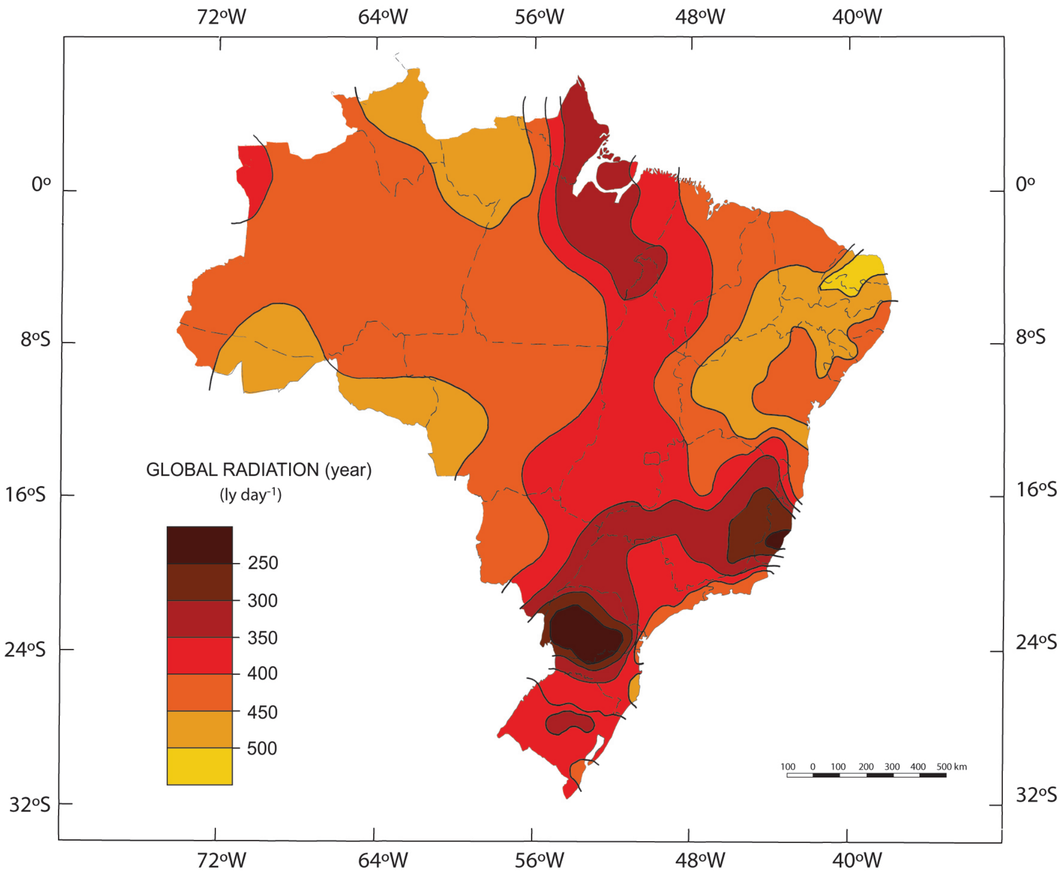

FIGURE 6 – Annual global radiation (ly day^{-1}) map.

On the other hand, the transmissivity is influenced by the latitude (which affects Q_o), the amount of water vapor and particles in suspension.

The south-north transect (Figure 8), which extends from the Uruguay border to the coast of the Ceará State, shows the following compartmentation:

• From the Uruguay border to Uberaba-MG: the maximum values of global radiation occur in the summer and the minimum values in the winter. In the mountain regions there is an influence of the orography;

• From Uberaba-MG to Pirapora-MG: there are no major differences between the maximum and minimum values; however, the absolute minimum values occur in the winter;

• From Pirapora-MG to Caetité-BA: irregular distribution with minimum values in the winter; there is an influence of the orography;

• From Caetité-BA to Bebedouro-PE: the distribution is very irregular, with maximum values in the summer and minimum ones in the winter;

• From Bebedouro-PE to the coast of Ceará: the distribution is relatively regular and uniform.

The west-east transect, from the Javari River (Peru border) to Recife-PE, shows the following compartmentation (Figure 8):

• From Javari River- AM to Arumanduba-PA: maximum and minimum values in the summer and the winter, respectively. The regularity is due to the latitude and uniform topography (with relief of the order of 200 m);

• From Arumanduba-PA to Teresina-PI: the distribution is very irregular; the maximum values occur in the second half of the year due to the rainfall regime;

• From Teresina-PI to Recife-PE: the relief is rugged. The maximum values occur from August to April and the minimum ones occur in the winter. Variations in this pattern are due to local effects, although the values are not very different throughout the year.

There are some similarities between this work and the study by MOTA et al. (1977), at

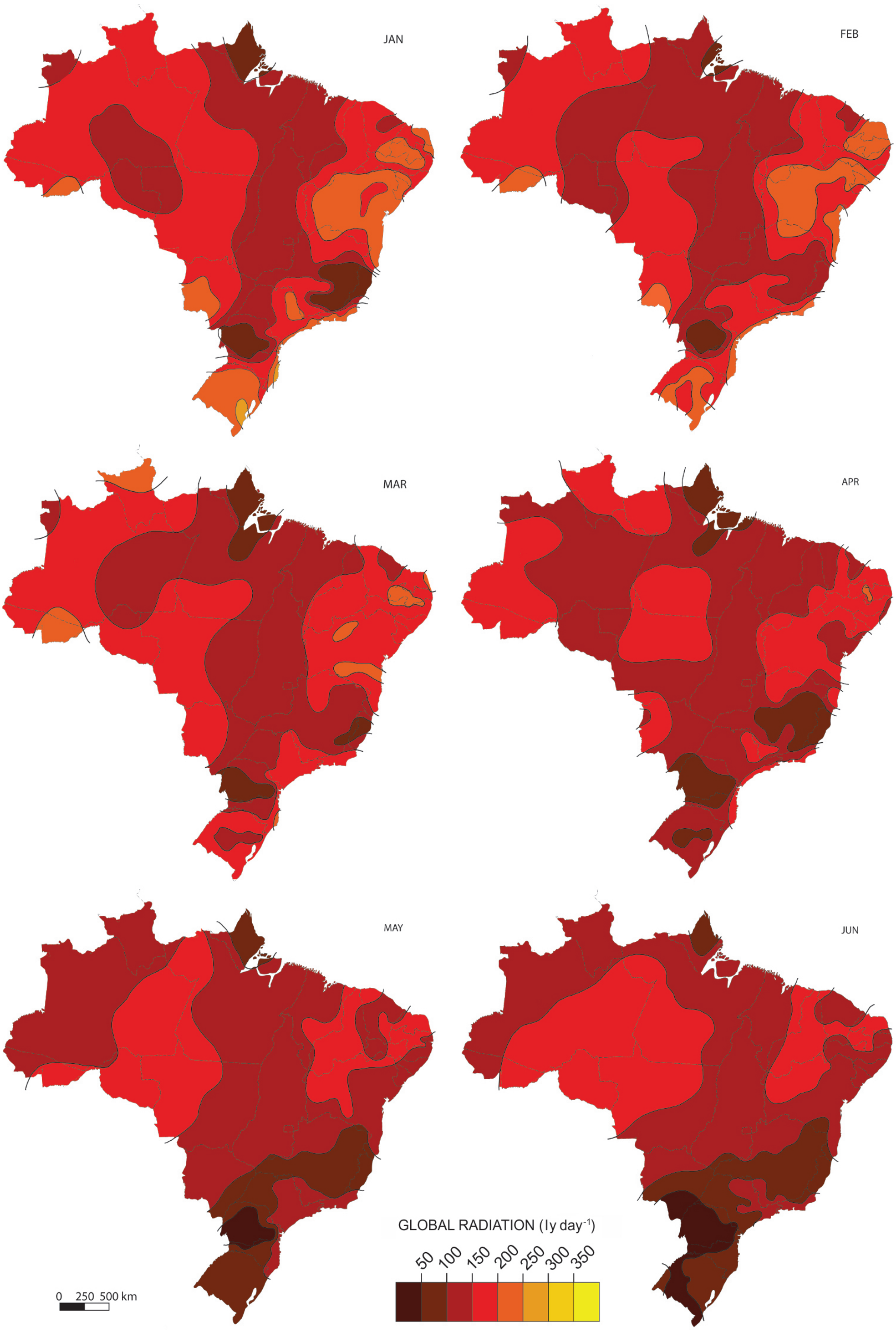

FIGURE 7 – Monthly global radiation (ly day^{-1}) maps (January - June).

FIGURE 7 (continuation) – Monthly global radiation (ly day^{-1}) maps (July - December).

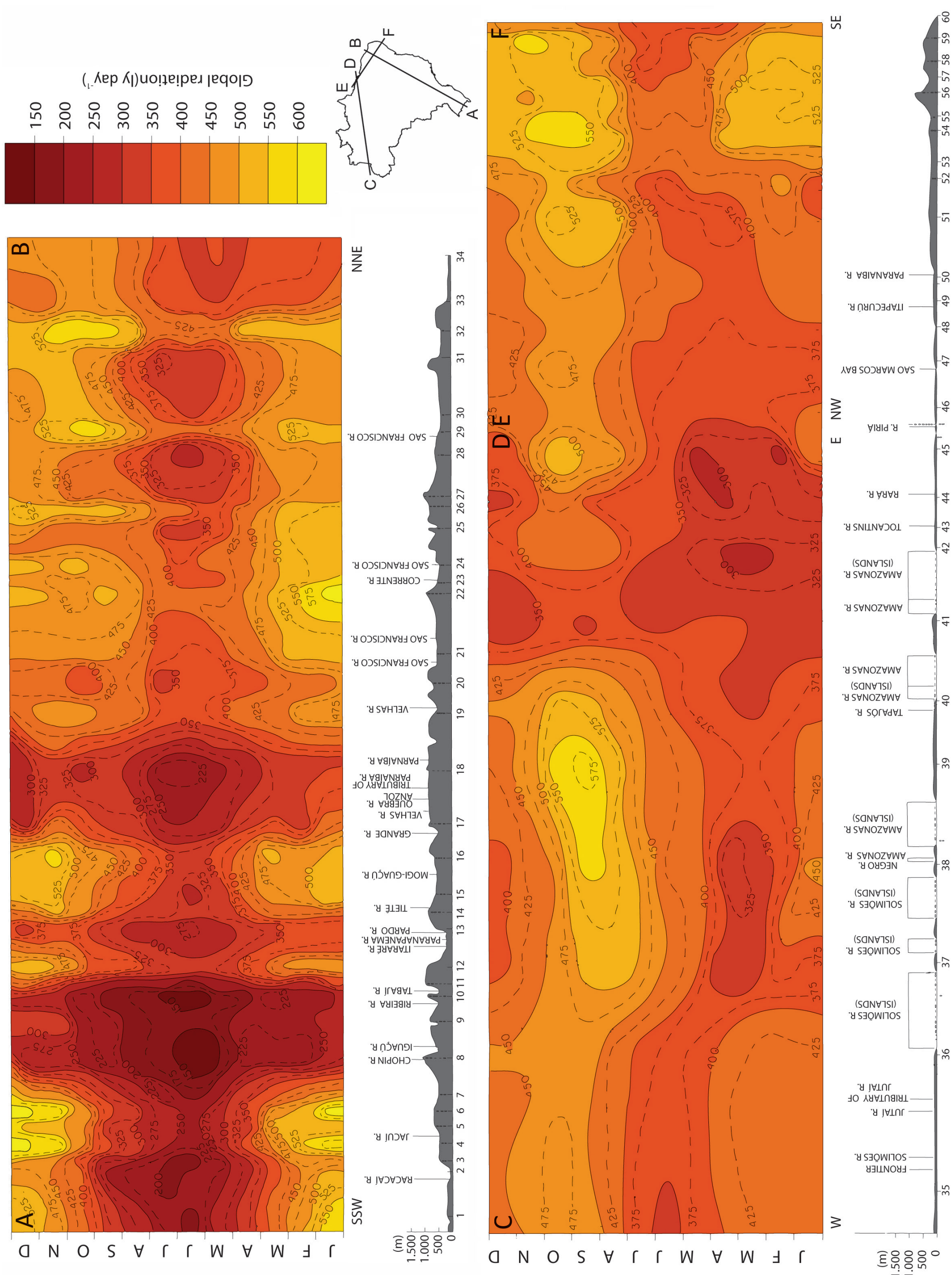

FIGURE 8 – Temporal-spatial variation of the global radiation along the south-north (A-B) and west-east (C-D and E-F) transects (Figure 2). See identification of the stations (numbers along the profile) in the table 2.

annual level. Both maximum values occur in the semi-arid region (*Caatinga*).

NUNES et al. (1978) produced monthly maps of estimated global radiation based on the formulation of BENNETT (1975). There are some similarities with the present work, which is more evident for the maximum values than the minimum ones. We used measured values from 99 stations and estimated from other 105, while NUNES et al. (1978) used only estimated data from 180 stations.

VILLA NOVA & SALATI (1977) reported a 12% error in their global radiation data available in Brazil. In this analysis we found percentage errors of the same order of magnitude.

In this work, we performed a study of the frequency of the maximum percentage deviations between the measured and the estimated global solar radiation, using the Angström's equation (Table 5).

TABLE 5 – Absolute and relative frequency of maximum deviations between measured and estimated global solar radiation, using the Angström's formula.

Classes	Frequency (nº stations)	Percentage from total
< 5.0%	22	33.8
5.1 – 10.0%	34	52.3
10.1 – 15.0	8	12.3
> 15%	1	1.6
	65	100.0

Of the 65 meteorological stations, 56 had maximum percentage deviations below 10.0%.

4 SPATIAL VARIATION OF THE NET RADIATION

4.1 Introduction

The net radiation is the balance of the radiation. This is the result of the energy exchanges in the atmosphere, conditioned by the fluxes of radiation emitted by the Sun – predominantly in short waves – and by the terrestrial radiation emitted by the ground surface (long waves).

From the solar radiation that reaches the ground surface, part is reflected by the surface and the rest is absorbed. The higher the albedo (reflectivity), the lower radiation is absorbed and vice versa.

The importance in studying the net radiation (Q_n) is in the consumptive use of this energy. This is dissipated or consumed in the following processes: air heating or sensible heat (H), latent heat of evaporation (LE), soil heating (G) and biological processes (photosynthesis and others) (F).

The equation that summarizes the consumptive use of the net radiation is:

$$Q_n = H + LE + G + F \qquad \text{[Eq. 3]}$$

The heat flux in the soil (G) depends on the thermal capacity and the conductivity of the soil. Experimental measurements show that, in determining the radiation balance in one or more weeks (our case), the G value is very small and can be neglected.

The amount of energy used in the photosynthetic and biological processes is very small, of the order of 1-2% of the total, being also negligible.

Because the values of G and F are very small, in practice, the consumptive use of net radiation is:

$$Q_n = H + LE \qquad \text{[Eq. 4]}$$

The amount of heat to evaporate 1 mm of water is called latent heat of evaporation (LE). This parameter varies slightly with the temperature, being of approximately 59 calories to 1 mm of water.

Approximately 70-80% of the available net radiation is consumed in the evapotranspiration process. The remainder corresponds to the sensible heat that heats the soil and the air.

The laws governing the flow of heat in gases cannot be applied to predict the sensible heat flux in the atmosphere, because this is an open system. The air flow above the soil surface causes it to be continually renewed and blend with the higher layers.

The measurement of H is impossible in practice. To solve this problem, we used the Bowen's ratio to calculate the LE value.

The determination of the net available energy is indispensable for the calculation of evapotranspiration for irrigation, water balance and organization of agrarian and urban spaces.

By studying the work of BRUNT (1939) about long-wave balance (effective terrestrial radiation), PENMAN (1948) established the following equation for the determination of the net radiation:

$$Q_n = Q_g \cdot (1 - \alpha) - R_b \qquad \text{[Eq. 5]}$$

Where: $Q_g \cdot (1 - \alpha)$ refers to the short-wave balance, which is easily obtained. The long-wave balance (R_b) was focused on several works (LONNQVIST 1954, MONTEITH 1961, SWINBANK 1963 and LINACRE 1967).

The radiation balance was studied by MONTEITH & SZEICZ (1961), STANHILL et al. (1966), LINACRE (1969a, 1978), DAVIES & IDSO (1979) and NUNEZ (1980). Using sensor measurements from the NIMBUS-III satellite, RASCHKE & HAAR (1974) obtained the radiation balance at the global scale. Similar work was done by WINSTON et al. (1979) that mapped the net radiation, effective terrestrial radiation, albedo and absorbed radiation, using data collected from the NOAA satellites.

In Brazil there is no study about net radiation at national level – only at regional, local and microclimatic scales.

At the regional scale, we can cite the following works: VILLA NOVA et al. (1977) estimated Q_n values for the Amazon region using the PENMAN method (1948), for the study of potential evapotranspiration. JOHNSON (1982) compared the methods of Penman and Thornthwaite for the determination of evapotranspiration in the central-western region of Brazil; this work presents an estimate of the net radiation for this part of the territory. ORSELLI (1982) established monthly net radiation maps for Santa Catarina State, using the modified Brunt-Penman's formulation.

At the local scale: VILLA NOVA et al. (1966) established the radiation balance for Piracicaba-SP. OMETTO (1968) studied the relationships between net radiation, global radiation and sunshine, based on a year of measurements. TARIFA & MONTEIRO (1972) calculated the radiation balance for the region of Presidente Prudente-SP. MOTA (1976) established equations for Pelotas-RS. MORAES et al. (1977) studied the types of weather and radiation balance in the city of São Paulo, using IAG data.

At the microclimatic scale, VILLA NOVA (1973) established the energy balance in rice cultivation in Campinas-SP.

4.2 Methodology

4.2.1 Material and methods

The most widely used net radiometers for the measurement of net radiation are: "Net Exchange Radiometer" devised by GIER & DUNKLE (1951) and constructed by Beckman and Whitley; and the "Net Pyrradiometer" idealized by SCHULZE (1953) and manufactured by Middleton & Co. Ltd. - Australia. These instruments must be connected to the potentiograph, in order to record the net radiation.

The working principle of the former is similar to that of the Eppley pyranometer for global radiation. It consists of two sets of thermoelectric pairs (differential thermopile), mounted on the upper and lower parts of a black plate, which absorbs the global radiation at the top and the effective radiation at the bottom.

The thermal energy of the sensors is dissipated by a fan, which passes a current of air over the sensitive elements. The problem is the impossibility of taking measurements on rainy days.

The "Net Pyrradiometer" consists of a thermopile in the form of a square plate, covered on both sides by polyethylene hemispheres. The hemispheres remain inflated due to the forced circulation of air or nitrogen that prevents the condensation of the water vapor and homogenizes the temperature inside the instrument. Due to the protection of polyethylene, the data acquisition is not subject to rainfall interference.

In Brazil, the nitrogen feed is replaced by an aquarium aerator. The compressed air from the aerator passes through a container filled with silica gel before being injected into the net radiometer. The circulation recommended by the manufacturer is controlled by the adjustment of the stroke of the aerator.

4.2.1.1 Estimation of terrestrial effective radiation

Due to the lack of stations for measuring the terrestrial effective radiation (R_b), it is generally estimated. In this work we adopted the formulation proposed by LINACRE (1967) that used the Swinbank's equation of 1963 for long-wave radiation flow downwards, with clear sky, adding the effect produced by the cloudiness. For completely clear sky conditions, LINACRE used:

$$\mathring{R}_b = \sigma \cdot T_a^4 \qquad \text{[Eq. 6]}$$

where:

$\mathring{R}_b$: effective terrestrial radiation with clear sky;

σ: Stefan-Boltzman constant ($1.191 \cdot 10^{-7}$ cal cm^{-2} day^{-1} K^{-4});

T_a: mean air temperature (K).

The correction of the effective terrestrial radiation to a clouded sky (R_b) is given by the expression (cal cm^{-2} min^{-1}):

$$R_b = \ddot{R}_b \cdot [g + (1 - g)] \cdot \frac{n}{N} \quad \text{[Eq. 7]}$$

where $[g + (1 - g)] \cdot \frac{n}{N}$ corresponds to the correction for cloudy skies; g is a parameter related to the height of the clouds and varies according to the author: 0.10 (PENMAN 1948); 0.20 (KRAMER 1958); 0.24 (IMPENS 1963) and 0.30 (FITZPATRICK 1965 apud LINACRE 1967). In this work, we used the average value (0.20) for the equation:

$$R_b = \ddot{R}_b \cdot [0.20 + (1 - 0.20) \cdot \frac{n}{N}]$$

$$R_b = \ddot{R}_b \cdot [0.20 + (0.80 \cdot \frac{n}{N})]$$

In numerical values:

$$R_b = (0.245 - 0.158 \cdot 10^{-10} \cdot T_a^4) \cdot [0.20 + (0.80 \cdot \frac{n}{N})]$$

According to LINACRE (1967), this equation can be approximated to (cal cm^{-2} min^{-1}):

$$R_b = 32 \cdot 10^{-5} \cdot (1 + 4 \cdot \frac{n}{N}) \cdot (100 - T) \quad \text{[Eq. 8]}$$

where T is in °C.

We adapted this equation to the daily level (ly day^{-1}):

$$R_b = [32 \cdot 10^{-5} \cdot (1 + 4 \cdot \frac{n}{N}) \cdot (100 - T)] \cdot 1440 \quad \text{[Eq. 9]}$$

Therefore, the data required for R_b estimation are the mean air temperature and the sunshine ratio.

All of the stations used in this work (175) had sunshine ratio data, but only 104 stations had the average air temperature data. To solve this problem, we used an estimate based on the work by VASCONCELLOS & TARIFA (1983).

In addition to the mentioned parameters, we used relative air humidity data (%) from the period 1931-60 of all stations, in order to compare the Linacres's equation of 1967 with the Brunt-Penman's formula.

4.2.1.2 Albedo estimation

The surface reflecting power, or albedo, was classified in three categories: albedos of natural vegetation, albedos of agricultural crops, and albedo of urbanized areas. For the natural vegetation, we adopted the types established by HUECK (1972) in his South American chart (21 types). Agricultural crops were divided into permanent crops (coffee and sugar cane) and annual crops (rice, cotton, corn, soybeans and wheat). The following metropolitan areas were considered as urban areas: Belém-PA, Belo Horizonte-MG, Brasília-DF, Curitiba-PR, Fortaleza-CE, Porto Alegre-RS, Recife-PE, Rio de Janeiro-RJ, Salvador-BA, and São Paulo-SP.

We adopted albedo values from the literature: OGUNTOYINBO (1970), STANHILL *et al.* (1966), GEIGER (1975) and DAVIES & IDSO (1979) for the natural vegetation; OGUNTOYINBO (1970), DAVIES & IDSO (1979) and MOTA (1977) for agricultural crops; OGUNTOYINBO (1970) for the urban areas.

For the albedo of the meteorological stations it was taken into account the main type of vegetation in their areas. There is certain homogeneity of (natural) vegetation in regions such as the Amazon and the semi-arid (*Caatinga*), but in the others our task was made very difficult by the intense land use. In areas where natural vegetation was replaced by crops, we obtained the albedo values for the meteorological stations based on the predominant culture in each municipality (IBGE 1977).

In this way, we obtained the albedos for 175 stations in Brazil (mean value: 0.19), which were used for the net radiation calculus.

4.2.1.3 Estimation of net radiation

The equation that represents the net radiation is:

$$Q_n = Q_g \cdot (1 - \alpha) - (Q_{L\downarrow} - Q_{L\uparrow}) \quad \text{[Eq. 10]}$$

Where:

Q_n: net radiation or balance of radiation (ly day^{-1});

Q_g: global radiation (ly day^{-1});

$Q_g (1 - \alpha) = Q_a$: global solar radiation absorbed by the surface, i.e. Q_a correspond to the short-wave balance;

α: surface albedo;

$Q_{L\downarrow}$: downward long-wave radiation (ly day^{-1});

$Q_{L\uparrow}$: upward long-wave radiation (ly day^{-1});

$(Q_{L\downarrow} - Q_{L\uparrow}) = R_b$: corresponds to long-wave balance, or effective terrestrial radiation (1y day^{-1});

So, finally, we have:

$$Q_n = Q_a - R_b \qquad \text{[Eq. 11]}$$

Then, we used the equation of LINACRE (1967) [Eq. 9] in [Eq. 11]:

$$Q_n = Q_g \cdot (1-\alpha) - [0.00032 \cdot (1+4 \cdot \frac{n}{N}) \cdot (100-T)] \cdot 1440 \qquad \text{[Eq. 12]}$$

This formula is quite simple and takes into account four parameters: global radiation (measured or estimated); the surface albedo (determination based on measurements), sunshine ratio (n: measured and N: calculated) and mean air temperature (measured or estimated).

4.2.2 The cartographic treatment

Monthly and annual charts and spatial-temporal diagrams of net radiation (Q_n) were produced using the same procedure for sunshine and global radiation. Isocontour maps of net radiation were traced based on 175 stations data, considering the relief, vegetation, hydrography, geomorphology, cloudiness and precipitation. The cloudiness values were based on surface observations and satellite data (MILLER & FEDDES 1971).

4.3 Results and discussion

The spatial and temporal distribution of the net radiation (Figures 9, 10) is conditioned by several factors that vary according to the peculiarities of each Brazilian region.

The north and center-west regions have high values, which varies a little from month to month. This is due to the uniformity of relief, albedo and little effect of latitude. The maximum values of the northeast region generally occur on the coast, from Rio Grande do Norte to southern Bahia.

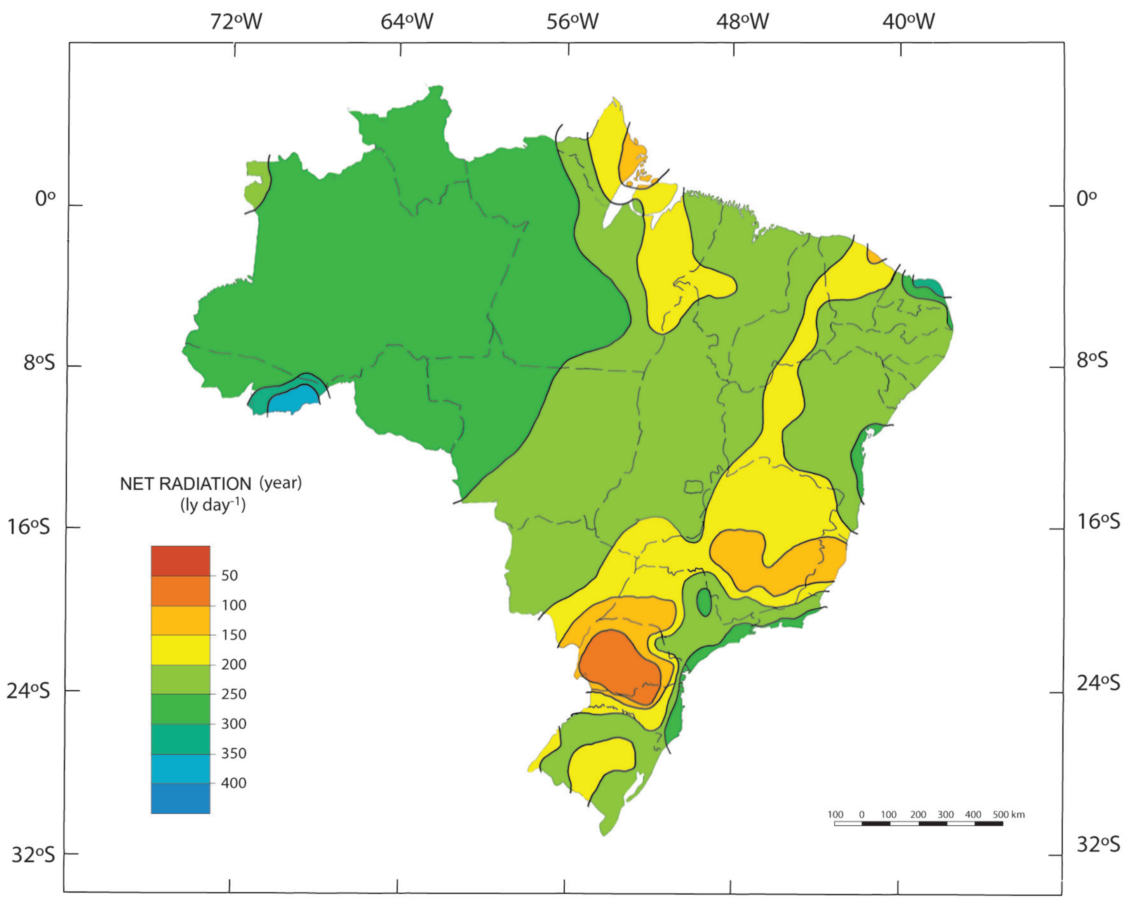

FIGURE 9 – Annual net radiation (ly day^{-1}) map.

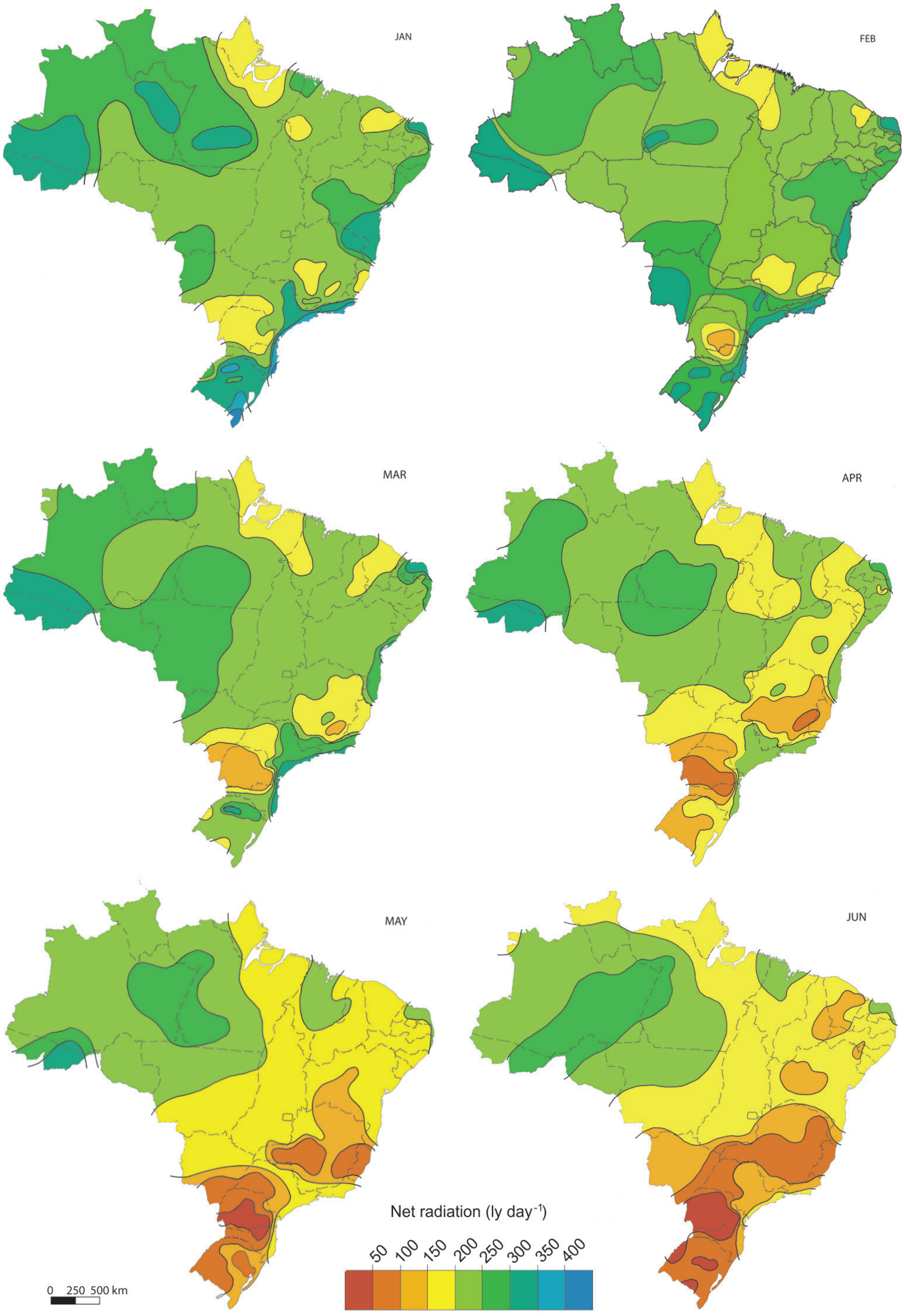

FIGURE 10 – Monthly net radiation (ly day^{-1}) maps (January - June).

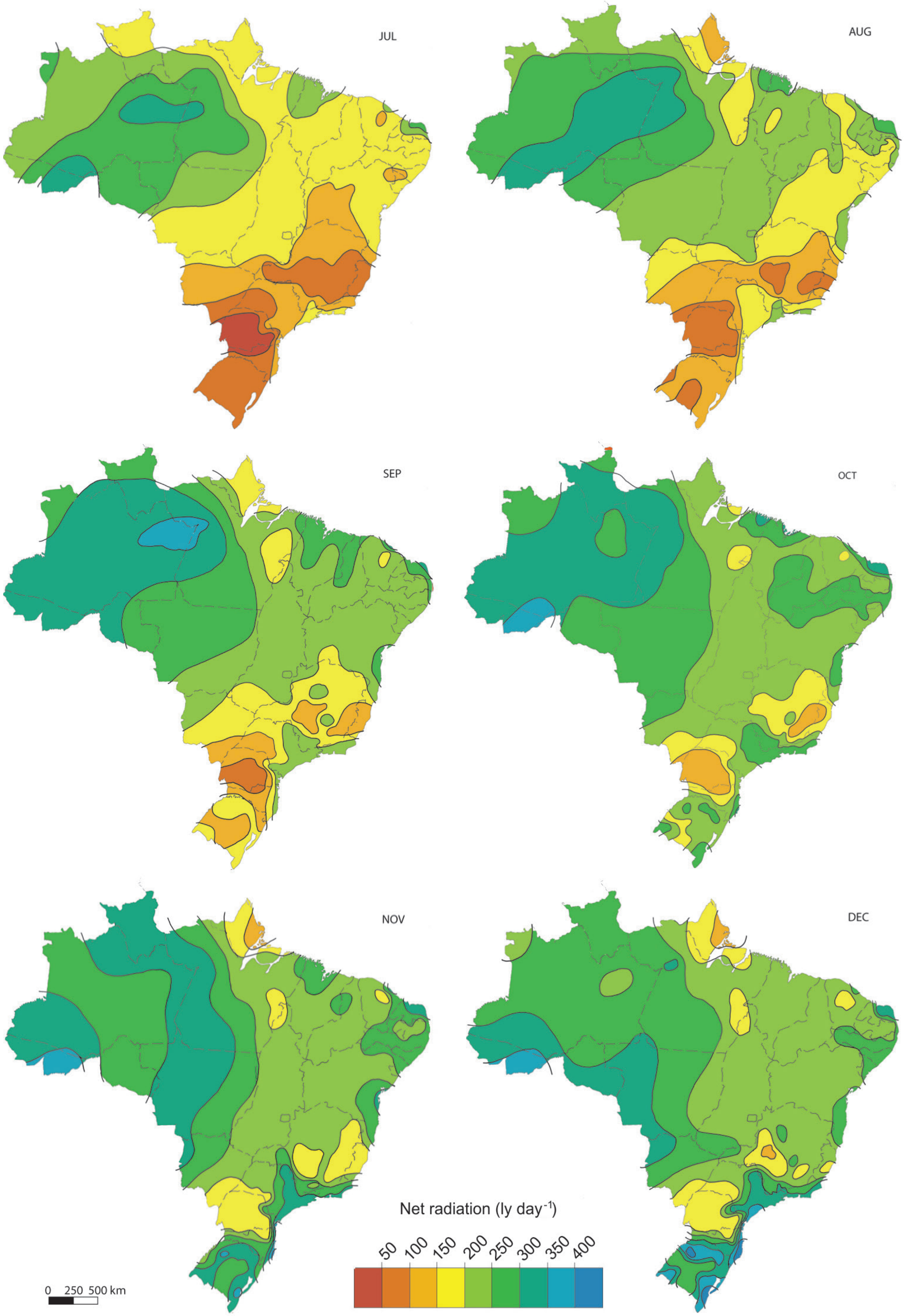

FIGURE 10 (continuation) – Monthly net radiation (ly day^{-1}) maps (July - December).

The lowest values found in the Brazilian territory are located in the southeastern and southern regions. Due to the cloudiness and albedo differentiated by the land use, and to the very rugged relief ("seas of hills" – *mares de morros*), the values vary a lot, from place to place and from month to month in the southeastern region.

In the southern region, lower values occur in the center and west of Paraná and north and west of Santa Catarina. There is a steep gradient from the coast to the towards on both states associated to the escarpments of the Serra do Mar and Serra Geral.

The effects of orography and nebulosity are also visualized in the temporo-spatial diagrams. The south-north transect (Figure 11) reveals the following compartmentation:

- From the Uruguay border to the region of Castro-PR: variations during the year, with the maximum values (October / March) being more than five times the minimum values, due to the latitude effect;
- From Castro-PR to Uberaba-MG: the maximum values also occur from October to March and the amplitudes between the highs and lows are much less accentuated;
- From Uberaba-MG to Irecê-BA: there is a very irregular distribution of the highest values;
- From Irecê-BA to the coast of Ceará (Jaguaruana): distribution is more uniform than the previous compartment; the lowest values of net radiation concentrated in the first half of the year, due to the higher precipitation.

The west-east transect (Figure 11) reveals the following compartmentation:

- From Rio Javari-AM (Peru border) to São Luis-MA: the values are similar throughout the year, with the lowest values in the first semester, which is the rainy season in the region;
- From S. Luis-MA to Recife-PE: the minimum values (all less than 200 $1y\ day^{-1}$) occur in the winter (May/July), when precipitation is high. The local effects due to the orography also occur in this region.

Given the lack of works on the Brazilian scale, our results can only be compared with regional scale studies.

JOHNSON (1982) evaluated the evapotranspiration and net radiation for the center-west of Brazil. However, because the method is different and the albedo data are discrepant, it can not be compared with our results.

ORSELLI (1982) presented monthly charts of net radiation, mapped on a scale of 1: 1,000,000, for Santa Catarina State. This work also could not be compared to this one due to the different method and the use of the Earth's planetary albedo.

The Brunt's equation modified by PENMAN (1948) is the most used to obtain the effective terrestrial radiation:

$$R_b = \sigma \cdot Ta^4 \cdot (0{,}56 - 0{,}09\ \sqrt{ed}) \cdot (0{,}1 + 0{,}9 \cdot \frac{n}{N})$$

σ : Stefan-Boltzmann constant (1.191 x 10^{-7} cal cm^{-2} d^{-1} K^{-4});

T_a: mean air temperature (K);

ed: actual water vapor pressure (daily average) (mmHg);

$\frac{n}{N}$: sunshine ratio;

This equation uses air temperature, relative humidity (to find the vapor pressure) and sunshine ratio data. The relative humidity is not measured in all the meteorological stations (only ca. 100). Due to this difficulty, it was not possible to use the Brunt-Penman's equation. Then we opted for the Linacre's formulation of 1967, previously seen (Eq. 12). This equation, which is much simpler, uses data of air temperature and sunshine ratio.

Of the 175 stations only 100 had relative humidity data. We then calculated the net radiation values for these 100 stations by the use of Brunt-Penman's equation and found the following percentage differences between Q_n (LINACRE) and Q_n (BRUNT-PENMAN) (Table 6):

TABLE 6 – Percentage differences between Q_n (LINACRE) and Q_n (BRUNT-PENMAN)

Differences (%)	nº stations
< 10.0%	26
10.1 – 15.0%	48
15.1 – 20.0 %	17
> 20%	9
	100

According to DENMEAD (1976), the precision of the measurements of net radiation is of the order of 15-20%, whereas according to

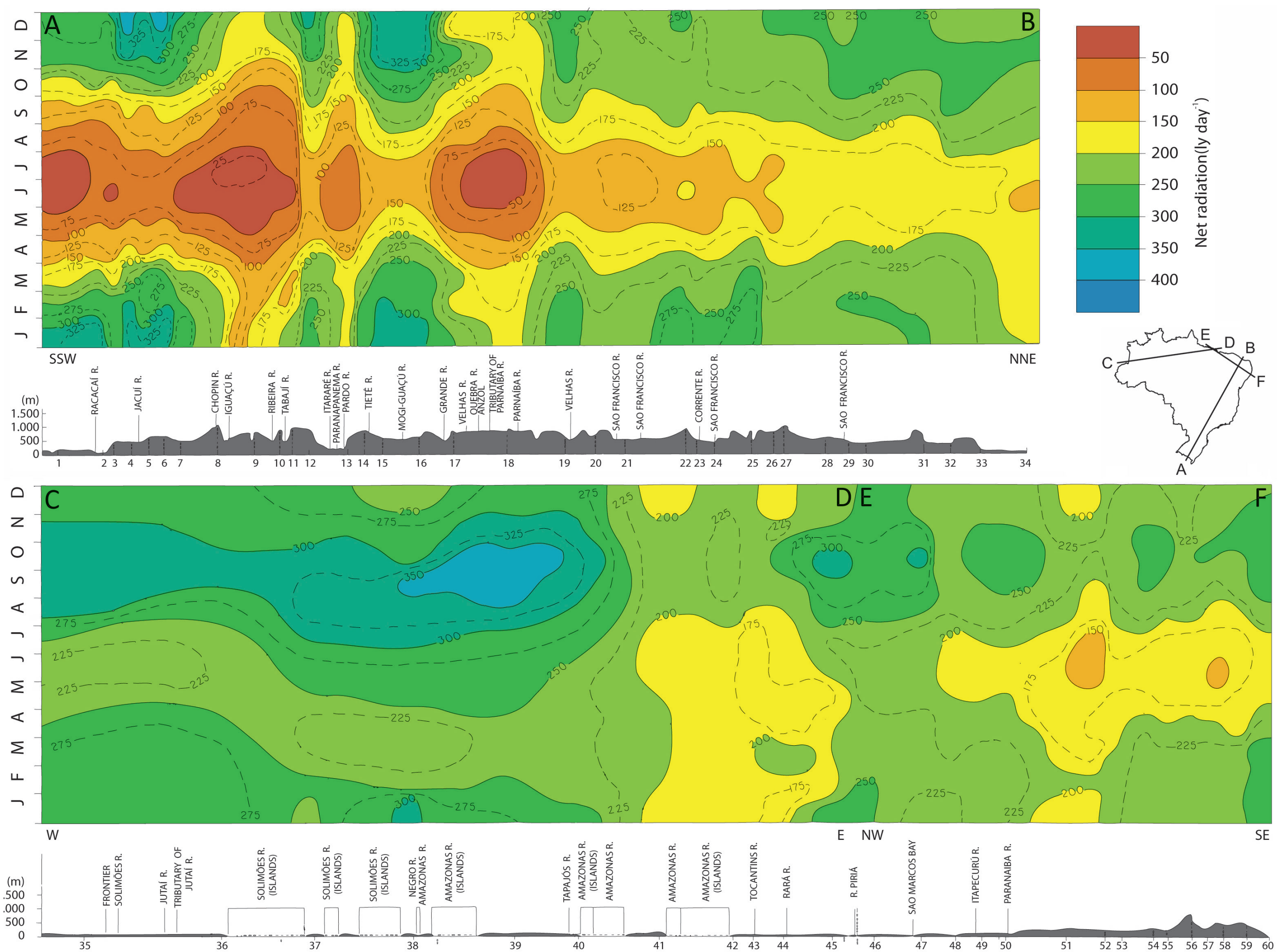

FIGURE 11 – Temporal-spatial variation of the net radiation along the south-north (A-B) and west-east (C-D and E-F) transects (Figure 2). See identification of the stations (numbers along the profile) in the table 2.

LINACRE (1969a and 1978), the precision of the estimates is about 20%. The results of this research are within the generally accepted limits.

There are few series of net radiation data in Brazil. OMETTO (1968) obtained a data series for the agricultural year of 1966-67 in Piracicaba-SP. By adopting the 0.20 albedo employed by that author, we applied the LINACRE (1967) formula for the Piracicaba data at the same agricultural year. We found a correlation of 0.95 between the values of estimated net radiation and OMETTO measurements (Figure 12).

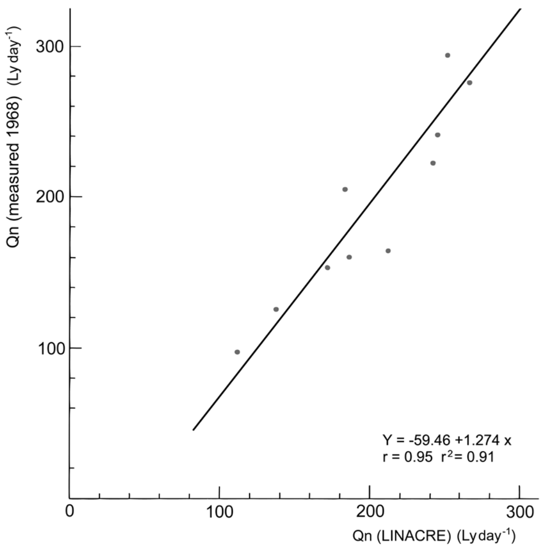

FIGURE 12 – Comparison between the estimated values obtained by Linacre's equation (1967) and the measurements obtained by OMETTO (1968) for Piracicaba - SP.

By using the Brunt-Penman's formula and the same data from OMETTO (1968), we found a correlation coefficient of 0.94. Table 7 shows OMETTO measurements (1968) and estimated values obtained by the equations of LINACRE (1967) and BRUNT-PENMAN.

The linear regression equations and the correlation coefficients were as follows: Y: measures; X1: Linacre's of 1967; X2: Brunt-Penman's equation of 1948, where:

$$Y = (1.2742 \cdot X1) - 59.458 \qquad r = 0.953 / r^2 = 0.91$$

$$Y = (1.1033 \cdot X2) - 13.528 \qquad r = 0.939 / r^2 = 0.83$$

Based on these results, we can affirm that the Linacre's equation of 1967 is valid for the estimation of the net radiation. At the monthly scale, this approach evaluates Q_n with equal or slightly greater precision than the classic Brunt's equation, modified by PENMAN (1948).

TABLE 7 – Relative deviations between the net radiation measured by OMETTO (O) and those estimated by the equations of LINACRE (L) and BRUNT-PENMAN (B).

Months	*Q_n (ly day^{-1})*			*Deviations (%)*	
	O(*)	*L*	*B*	*(L-O)*	*(B-O)*
Jan	277	266	276	-4.0	-0.4
Feb	242	245	258	+1.2	+6.6
Mar	224	241	251	+7.6	+12.1
Apr	165	212	200	+28.5	+21.2
May	154	172	148	+11.7	-3.9
Jun	98	112	108	+14.3	+10.2
Jul	126	138	121	+9.5	-4.0
Aug	160	186	150	+16.2	-6.3
Sept	206	193	173	-6.3	-16.0
Oct	295	252	245	-14.6	-17.0
Nov	329	313	302	-4.9	-8.2
Dec	340	283	286	-16.8	-15.9

(*) measures in the agricultural year 1966-67, Piracicaba-SP. Albedo: 0.20.

5 CONCLUSIONS

Based on the results obtained in the charts and time-space diagrams presented in this work, the following conclusions are valid:

1) The use of Angström's equation of 1924 for the estimation of global radiation was within the precision required by the temporal and spatial scales of this work.

2) When used for determination of the effective terrestrial radiation, the Linacre's equation (1967) was comparable to the Brunt-Penman's equation.

3) In some regions, the irregular density of the station network hinders larger scale studies.

4) The geographical factors, such as the relief and land use, have an important influence on the parameters, as observed by the analyses of the maps and temporal-spatial diagrams.

5) The cloudiness, rainfall and transmissivity of the atmosphere are the most important climate parameters for the sunshine, global radiation and net radiation.

6) In general, the north, northeast and central-west regions present the highest values of sunshine, global radiation and net radiation.

7) The minimum values of sunshine, global radiation and net radiation are located in the Rio Doce Valley (MG/ES) and central-west of Paraná and Santa Catarina.

8) Although having areas with low values, the general potential of our country is very high: 2522 h year^{-1} of sunshine (~ 7.0 h day^{-1}); 427 ly day^{-1} of global radiation; and 237 ly day^{-1} of net radiation (mean values of all seasons).

9) Comparing with the measures by OMETTO (1968) in Piracicaba, the Linacre's equation of 1967 was shown to be quite satisfactory with a correlation coefficient of 0.95.

10) The spatial temporal diagrams show the different behavior of sunshine, global radiation and net radiation along the south-north and west-east transects in Brazil.

11) The results of this research work can be applied to the planning of urban and agrarian spaces at the regional level.

12) The elements of the radiation balance can be used at the local and regional scales.

13) The radiation balance varies from one place to another and throughout the year in the southeast and south regions, due to the anthropic action (differentiated land use).

14) A pronounced gradient was observed for the values of global radiation and net radiation in the south and southeast regions, due to the orography.

15) Due to the limitations imposed by the amount of data and the irregular distribution of the network of stations, the maps of sunshine, global radiation and net radiation presented here should be considered as valid estimates to improve the knowledge of the climate realities at the regional scale.

16) In this work the values for global radiation and net radiation were expressed in langley (ly day^{-1}). To be transformed into the unit W m^{-2}, it is necessary to use the equation: W m^{-2} = ly * 0.485.

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APPENDIX: Real sunshine, temperature, global radiation, terrestrial effective radiation and net radiation data – available online at http://dx.doi.org/10.5935/0100-929X.20170009

Authors' addresses:

Frederico Luiz Funari – Laboratório de Hidrometeorologia, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, Av. Miguel Stéfano, 4200, Água Funda, CEP: 04301-904, São Paulo, SP, Brasil. *E-mail*: ffunari@uol.com.br

José Roberto Tarifa – Laboratório de Climatologia (Labclima), Departamento de Geografia, Universidade Federal de Mato Grosso, Campus Rondonópolis, Av. dos Estudantes, 5.055, Bairro Cidade Universitária, CEP: 78736-900, Rondonópolis, MT, Brasil. *E-mail*: jrtarifa@gmail.com

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