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Solar energy scenarios in Brazil, Part one: Resource assessment

F.R. Martins [a,*], E.B. Pereira [a], S.A.B. Silva [a], S.L. Abreu [b], Sergio Colle [c]

[a] Centre for Weather Forecast and Climate Studies, Brazilian Institute for Space Research, CPTEC-INPE, P.O. Box 515, São José dos Campos, SP 12245-970, Brazil
[b] Centro Federal de Educação Tecnológica de Santa Catarina—CEFET-SC, Rua José Lino Kretzer 608, São José, SC 88103-310, Brazil
[c] Solar Energy Laboratory, University of Santa Catarina—LABSOLAR-UFSC, Campus Universitário Trindade, Florianópolis 88040-900, Brazil

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ABSTRACT

The "Solar and Wind Energy Resource Assessment" (SWERA) project was an international project financed by GEF/UNEP, which aimed at providing a consistent and accessible database to foster the insertion of renewable energies on the energy matrix of developing countries. This paper presents the solar energy resource assessment generated during the SWERA project by using the radiative transfer model BRASIL-SR fed with satellite and climate data. The solar irradiation estimates were validated by comparing with the ground data acquired in several sites spread out the Brazilian territory. Maps on $10 \times 10\,km^2$ spatial resolution were generated for global, diffuse and direct normal solar irradiation. Solar irradiation on a plane tilted by an angle equal to the local latitude was also generated at the same spatial resolution. Besides the solar resource maps, the annual and seasonal variability of solar energy resource was evaluated and discussed. By analyzing the Brazilian solar resource and variability maps, the great potential available for solar energy applications in Brazil is apparent, even in the semi-temperate climate in the southern region where the annual mean of solar irradiation is comparable to that estimated for the equatorial Amazonian region.

1. Introduction

Energy is essential for the social development and economic growth of any nation. The human quality of life is strongly related to the per capita consumption of energy, which has been rising steadily for the last few decades in the developing countries as a consequence of the growth in agricultural and industrial activities, the improvement of social conditions and the introduction of new technologies. The net result of this has been that the energy demand has multiplied manifold and it can be no longer satisfied by the traditional inefficient energy technology (Goldemberg and Villanueva, 2003).

In addition to that, the link between current energy consumption and environmental damage has been demonstrated. The last IPCC report (IPCC, 2007) reinforces that fossil fuel energy consumption is the major contributor for global warming due to greenhouse gas emissions. Other studies stated that alternative energy sources should be implemented over the next 20 years in order to help reduce greenhouse gas emissions and to enhance the energy security (Sims, 2004).

However, mid- and long-term energy planning requires reliable information on many natural resources focusing on the renewable energy policy. Usually, investors, risk capital enterprises and independent energy producers are not aware of the available renewable energy options and tend to avoid the risk of activities dealing with renewable energy projects in developing countries where reliable and suitably detailed data are almost non-existent. In summary, the main knowledge obstacle to enhance investments in renewable energy production in developing countries is related to the lack of a reliable renewable energy resource assessment. The resource assessment data together with information on the resource variability and confidence levels linked to several natural and non-natural variables (such as climate, topography and man-made impacts in environment) are essential to develop projects in renewable energy usage.

The United Nations Environment Programme (UNEP) and Global Environmental Facility (GEF) gave support to a scientific program in order to build up a reliable database in solar and wind energy resource. The "Solar and Wind Resource Assessment" (SWERA) project aims at fostering the insertion of renewable energies in the energy matrix of developing countries. The SWERA project is assembling high-quality information on solar and wind energy resources into consistent geographic information system (GIS) analysis tools for developing countries divided into three great regional groups: Africa, Latin America and Asia. The project is mainly intended for the government and private sectors involved in the development of the energy market and it shall

* Corresponding author. Tel.: +55 12 3945 6778; fax: +55 12 3945 6810.
E-mail address: fernando@dge.inpe.br (F.R. Martins).

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Nomenclature

CCI	cloud cover index
$I_{d,y}$	daily solar flux for day d of the year y
$I_{sea,y}$	seasonal mean of daily sum of global solar flux for a specific season of the year y
I_y	annual mean of daily sum of global solar flux for the year y
L	visible radiance measured by satellite sensor
L_{clr}	visible radiance measured by satellite sensor in clear sky condition
L_{cld}	visible radiance measured by satellite sensor in overcast sky condition
$n1$	day number (or Julian day) of the first day for a specific season
$n2$	day number (or Julian day) of the last day for a specific season
N_d	number of days with daily sums of global solar flux available along 1 year
$N_{d,sea}$	number of days with daily sums of global solar flux available along one specific season in the year y
N_y	number of years in the 1995–2005 period with annual mean of daily sums of global solar flux available
SD_d	mean quadratic difference between the daily global solar flux for day d of the year y and annual mean of daily global solar flux for the same year
$SD_{sea,y}$	mean quadratic difference between the daily global solar flux for day d of the year y and seasonal mean of daily global solar flux for the same year
V_{annual}	annual variability for daily sums of global solar flux
$V_{d,y}$	intra-annual variability for the day d of the year y
$V_{seasonal}$	seasonal variability for daily sums of global solar flux for a specific season
$V_{sea,y}$	seasonal variability for daily sums of global solar flux for a specific season in the year y

enable policy makers to assess the technical, economic and environmental potential for large-scale investments in renewable and sustainable technologies. More details on general goals and main results and products for Brazil and other countries can be found at http://swera.unep.net/.

This paper is the first of three articles presenting the main solar energy products achieved along the SWERA project for Brazil. It presents the solar energy resource assessment generated for Brazilian territory based on satellite-derived data. The second paper will present the scenarios for photovoltaic (PV) applications in Brazil prepared by using the solar energy resource database described in this article. Then, the last paper will conclude, presenting some scenarios for thermal solar applications.

2. SWERA project in Brazil

The Centre for Weather Forecast and Climate Studies of the Brazilian Institute for Space Research (CPTEC/INPE) coordinated the SWERA activities in Brazil. The Solar Energy Laboratory of University of Santa Catarina (LABSOLAR/UFSC), the Brazilian Center of Wind Energy (CBEE), the Brazilian Centre for Research in Electricity (CEPEL), the State University of New York (SUNY) and the US Renewable Energy Laboratory (NREL) are partners in this enterprise.

The solar and wind energy resources data for Brazil generated by the SWERA partners were put together with a variety of useful geographic and socio-economic information such as population distribution, per capita income, maps of railroads, rivers, roads, distribution lines of electricity, industry locations, protected areas, power plants and others. All available data are archived in GIS format (geo-referenced data) and can be used for decision making and policy analysis as well as identifying potential areas for wind and solar energy projects. The GIS database aims at providing the government and the private investor with a simple and easily available tool to perform otherwise intricate queries to evaluate the risk and benefits of the potential use of solar and wind energy resources.

The solar resource data available for Brazil in SWERA DATA ARCHIVE comprises the following products: (a) the monthly averages for global and direct solar radiation provided by the Climatological Solar Radiation (CSR) model in $40\,km \times 40\,km$ resolution developed by NREL and (b) the seasonal and annual averages for global, diffuse, direct normal and latitude-tilted surface provided by the BRASIL-SR model in $10 \times 10\,km^2$ developed by CPTEC/INPE and LABSOLAR/UFSC.

The NREL maps were prepared by using information on the 40-km resolution gridded cloud cover data (real-time nephanalysis—1985–1991) provided by the US National Climatic Data Center together with atmospheric water vapor, trace gases and aerosols data as input to NREL's CSR model (Maxwell et al., 1998).

The BRASIL-SR model, developed by CPTEC/INPE and LABSOLAR/UFSC (Martins, 2001; Pereira et al., 2000), is a physical method based on a radiative transfer model described in Stuhlmann et al. (1990). It uses cloud cover data acquired from geostationary satellite images together with climate data to parameterize the radiative processes in the atmosphere. The high-resolution solar resource maps produced using the model BRASIL-SR will be presented and discussed in detail in this paper.

3. Solar energy resource maps for Brazil

All the maps presented here show the average of daily sums of estimated solar irradiation provided by the model BRASIL-SR for the 10-year period (from 1995 till 2005) in $10 \times 10\,km^2$ spatial resolution.

3.1. Model BRASIL-SR

The radiative transfer model BRASIL-SR was used to obtain solar flux estimates at the surface. It combines the "Two-Stream" approach to solve the radiative transfer equation along with climate data and satellite images (Pereira et al., 2006). Fig. 1 shows the model's flowchart. The procedure to obtain solar estimates is divided into three steps: (i) assimilation of climate and satellite data; (ii) numerical resolution of the radiative transfer equation for clear and overcast sky conditions using the "Two-Stream" approach; and (iii) calculation of each solar irradiation components for any sky condition (global, direct and diffuse).

The required database for first step comprises six variables: air temperature at the surface, relative humidity, atmospheric visibility, surface albedo, surface elevation and effective cloud coverage.

In the second step, the radiative processes are modeled by dividing the atmosphere in 30 vertical layers and the solar

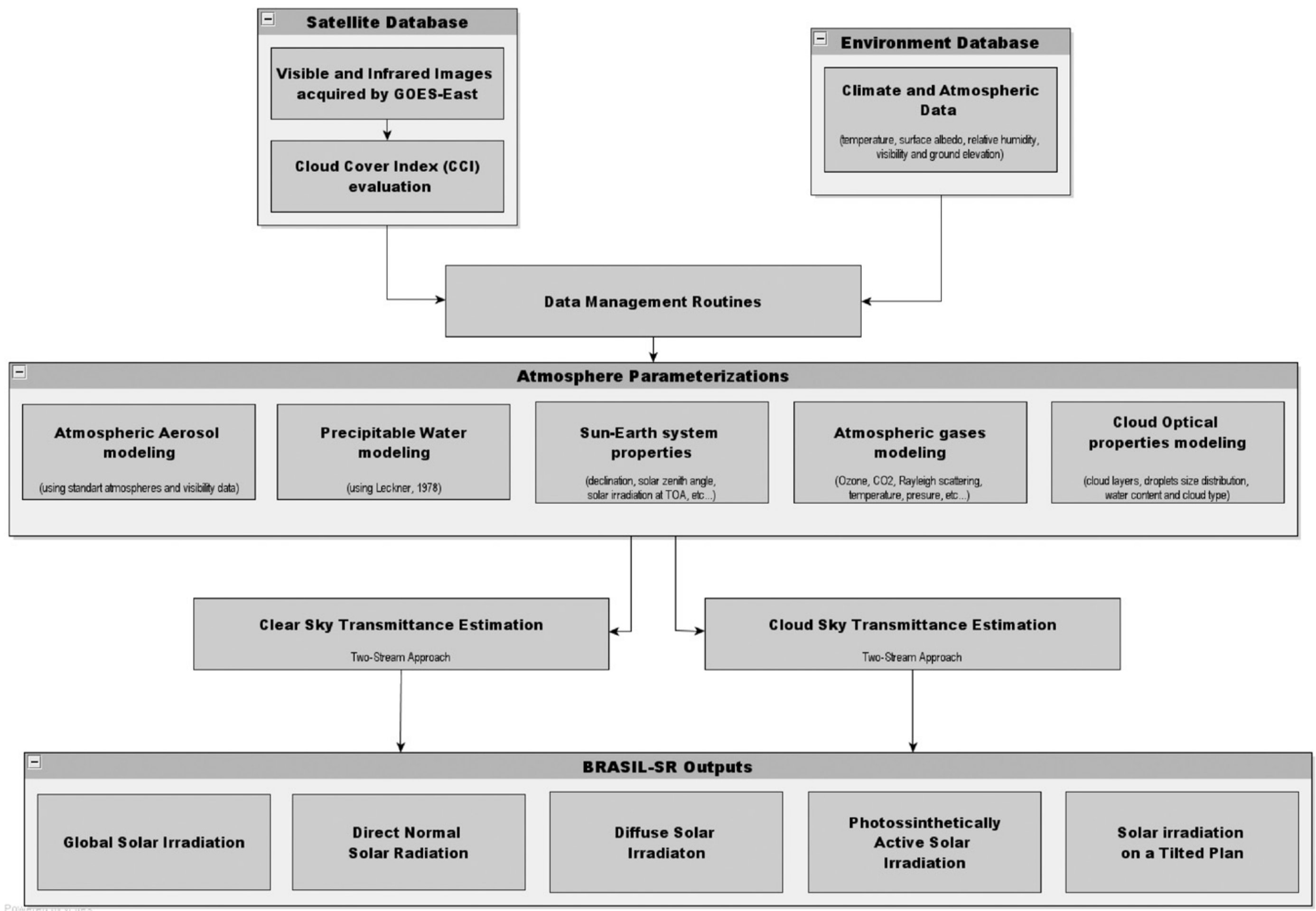

Fig. 1. Flowchart of radiative transfer model BRASIL-SR.

radiation spectral interval (0–4 μm) is split into 135 subintervals. The thickness of each atmospheric layer as well as the vertical profiles of temperature and atmospheric gas concentrations are established for the standard atmosphere selected as a function of the air temperature at the surface. The model employs the continental profile of atmospheric aerosols for altitudes from 0 to 50 km, corrected for the first 5 km through climatologic visibility values (Pereira et al., 2006).

The terrain topography was obtained from the GTOPO30 database made available by the US Geological Survey (http://edc.usgs.gov/products/elevation/gtopo30html/). This database is in a grid format with a horizontal resolution of 30 arcsec (approximately 1 km) and topographic precision up to 100 m, which is more than adequate for solar radiation modeling. Fig. 2 shows the elevation map for the Brazilian territory.

The global solar irradiation at the surface in any sky condition is obtained from a linear relation between the solar radiation flux at the surface in clear and overcast sky conditions. The cloud cover index (*CCI*) is the weighting factor between those extreme conditions and the confidence and reliability of the *CCI* is a chief factor to obtain solar estimates with good accuracy (Martins et al., 2007). The *CCI* contains information on spatial distribution and optical thickness of clouds and it was obtained by using Eq. (1) for each pixel from GOES images. The L stands for the visible radiance measured by the satellite sensor, and L_{clr} and L_{cld} are, respectively, the visible radiances measured in the same wavelength spectral range at clear and overcast sky

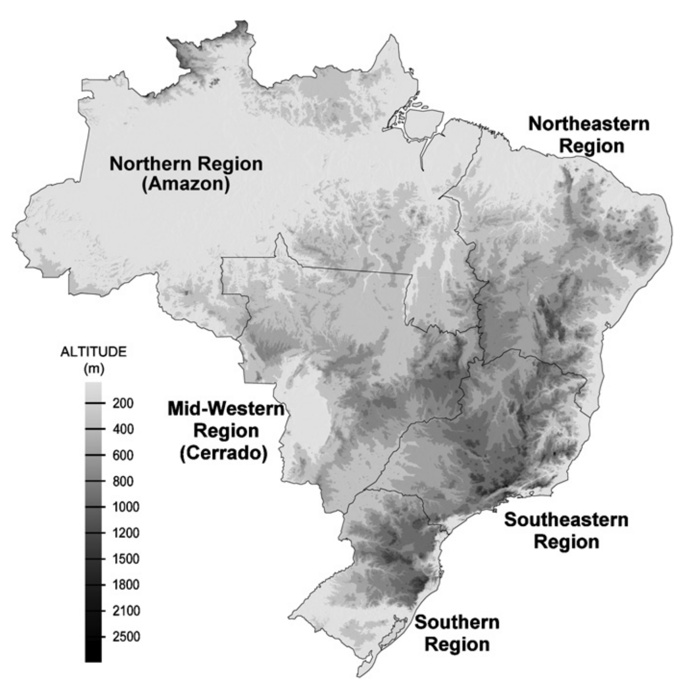

Fig. 2. Topography map for Brazilian territory including the borders of Brazilian geographical regions.

conditions.

$$CCI = \frac{[L - L_{clr}]}{[L_{cld} - L_{clr}]} \quad (1)$$

The L_{clr} and L_{cld} values for each image pixel are obtained by statistical analysis of satellite images (Martins et al., 2007). The key point in this methodology is its independence from the calibration factors and electronic degradation of satellite sensors. It was assumed that *CCI* equal to 1.0 denotes overcast sky with altostratus (As) clouds. Previous studies showed that As clouds are the most common cloud type in continental areas in the latitude range where Brazil is located (Warren et al., 1986).

It was assumed that the entire cloud coverage is formed by a single type of cloud with its base at 500 mb and uniformly distributed in two atmospheric layers in order to solve the solar radiative transfer equation for the overcast sky condition. The Stephens parameterization was assumed to determine the total extinction coefficient and the total liquid water content of the cloud (Stephens, 1978).

The diffuse solar radiation is determined by subtracting the direct component from the global solar radiation at the horizontal surface. The normal direct irradiation (DNI) is estimated assuming that the absorption by clouds is not significant and that the contribution of scattering of the solar radiation by clouds may be added to the atmospheric transmittance in clear sky conditions. The solar irradiation on a tilted plane was obtained by using the Perez et al. (1987) methodology.

The reliability of the solar irradiation estimates provided by model BRASIL-SR was evaluated in two tasks: (i) through comparison with estimates provided by the core radiation transfer models adopted by the SWERA to map the solar energy in other countries taking part in the project and (ii) through the comparison among the estimates with solar radiation flux measured at the surface (ground truth). The results obtained in the first task demonstrated that BRASIL-SR presents a similar performance as any other radiative transfer model adopted in SWERA (Beyer et al., 2004; Martins, 2003).

In the second task, the solar flux estimates provided by the BRASIL-SR were compared with measured values acquired at several ground sites spread along the Brazilian territory—Project SONDA (Martins et al., 2005) and AWS (Automated Weather Stations) operated by CPTEC/INPE (www.cptec.inpe.br/aws). The model BRASIL-SR achieved a similar performance in all geographic regions of the country with a slight overestimation of the global solar flux—mean bias error (MBE) roughly 6%. The root mean square error (RMSE) was about 13% throughout the Brazilian territory. Table 1 presents a summary for mean deviation observed in solar radiation estimates provided by BRASIL-SR. The larger deviations were observed in the Amazon region, which presents larger precipitation all through the year and the ground stations maintenance was more complex reducing the confidence of ground data (Pereira et al., 2006).

The direct beam solar irradiation (DNI) values provided by BRASIL-SR overestimated the ground data and presented larger deviations (MBE $\approx$15% and RMSE $\approx$22%). The simple parameterization used to model the cloud transmittance of the direct beam is responsible for the overestimation of direct beam irradiation, mainly in the overcast days (Pereira et al., 2006). Unfortunately, only few ground sites collect direct solar beam radiation in Brazil with the high quality required to be used in model validation. Table 2 presents the estimate deviations for all the ground sites available for DNI validation.

Table 1
Summary of the deviations presented by global solar estimates provided by BRASIL-SR in each Brazilian geographic region

Geographical region	MBE (Wh/m^2)	MBE (%)	RMSE (%)	Correlation factor
Northern	353.48	7	15	0.85
Northeastern	306.75	6	13	0.97
Midwestern	272.11	5	13	0.89
Southeastern	249.10	5	14	0.93
Southern	259.49	5	12	0.97

The last column presents the correlation factor among ground data and model estimates.

Table 2
Deviations presented by DNI estimates provided by BRASIL-SR when compared with the ground data acquired in SONDA network

Ground site	MBE (Wh/m^2)	MBE (%)	RMSE (%)	Correlation factor
São Martinho da Serra	872.8	13.0	19.7	0.96
Florianópolis	1147.5	22.7	29.2	0.95
Petrolina	718.4	12.7	18.3	0.96
All sites	903.2	15.1	21.6	0.95

The last column presents the correlation factor among ground data and model estimates.

3.2. Global solar irradiation

Fig. 3 presents annual and seasonal averages of daily global solar irradiation in Brazil. In spite of the different climate and environmental characteristics of the Brazilian territory, one can observe that the global irradiation is fairly uniform. The maximum value—more than 6.5 kWh/m^{2}day—occurs in the semi-arid area of the Brazilian Northeastern region (around 10°S/43°W). This area presents a semi-arid climate with low annual precipitation (around 300 mm) and the lowest mean cloud cover of Brazil (INMET, 2007) due to the influence of the tropical high pressure associated with the South Atlantic tropical anticyclone.

The minimum value, around 4.25 kWh/m^{2}day, was obtained for the coastal area of the Southern region of Brazil, which is characterized by a relatively large precipitation. The temperate climate and the influence of the cold systems associated with the Antarctic Polar anticyclone contribute to enhance the nebulosity in the region, mainly in winter months. Fig. 4 shows the climatology of annual precipitation and cloud cover for the Brazilian territory taking into consideration ground data collected from 1931 till 1990.

The annual sum of daily horizontal global solar irradiation in any Brazilian region (1500–2500 kWh/m^2) is greater than those for the majority of the European countries such as Germany (900–1250 kWh/m^2), France (900–1650 kWh/m^2) and Spain (1200–1850 kWh/m^2) where projects to harness solar resources are greatly disseminated, some with huge government incentives (European Database for Daylight and Solar Radiation, 2007).

It is worthy of note that the Southern region is subjected to larger mean irradiances than the Northern region during the summer season notwithstanding the latter being much closer to the equator. This is explained by climate characteristics of Amazon region with large precipitation and persistent cloud cover during the summer months owing to the strong influence of the Intertropical Convergence Zone (ITCZ). The North and Central regions of Brazil receive the largest solar irradiances particularly during the dry season from July till September, when precipitation is low, and clear sky days predominate.

Fig. 5 shows the annual and seasonal variability of daily sums of global solar irradiation. The annual variability, V_{annual}, was defined here as the average of the intra-annual variability observed for each day of the year. The intra-annual variability, $V_{d,y}$, for the day d of the year y is defined as presented in Eq. (2). SD_d stands for the mean quadratic deviation of global solar

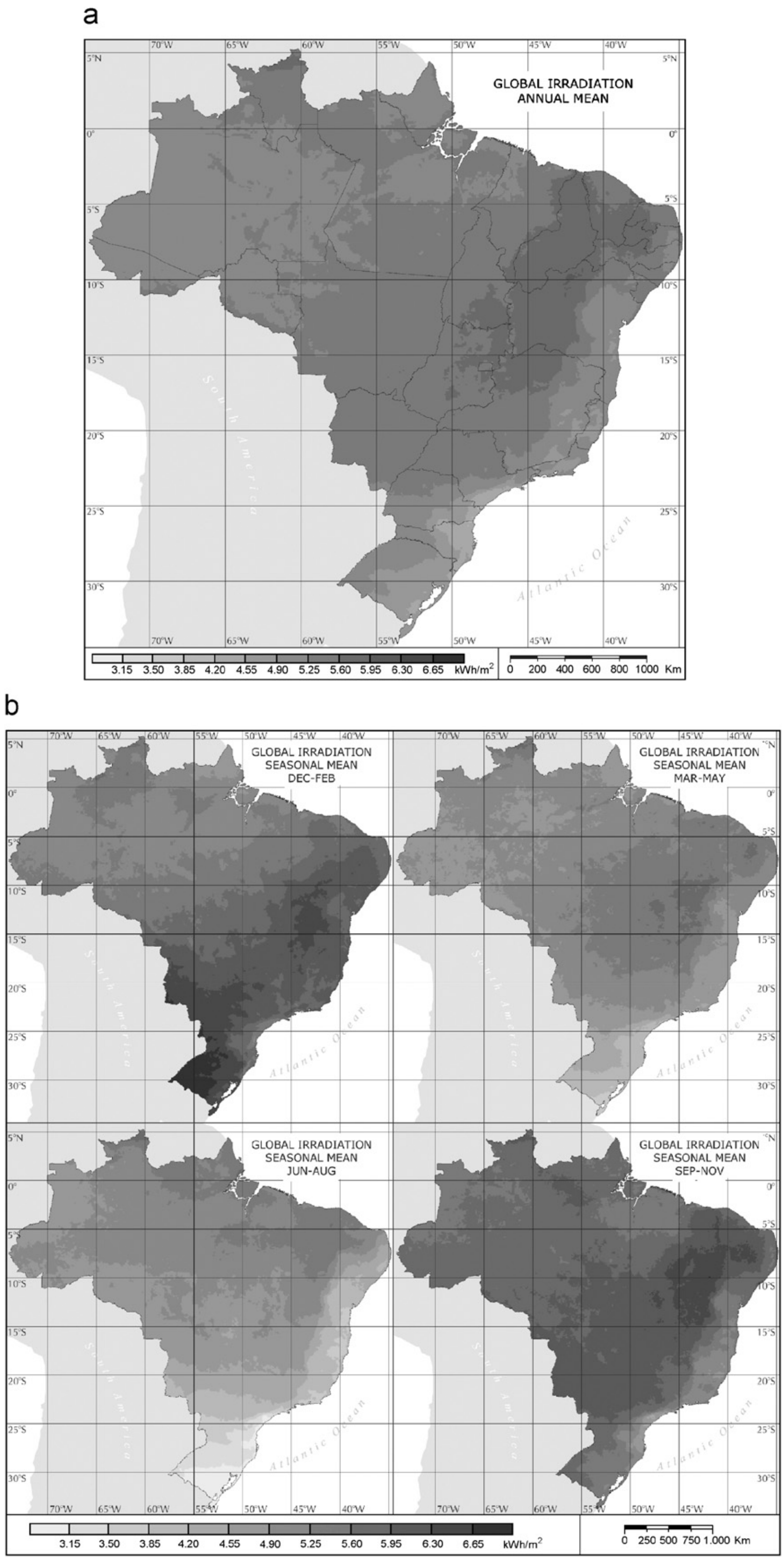

Fig. 3. (a) Annual average of daily sum of the global solar irradiation in Brazilian territory. (b) Seasonal averages of daily sum of the global solar irradiation in Brazilian territory. The summer season comprises the period from December till February. The period between March and May is related to the fall season. The winter encompass June to August, and the spring season starts at September and ends at November.

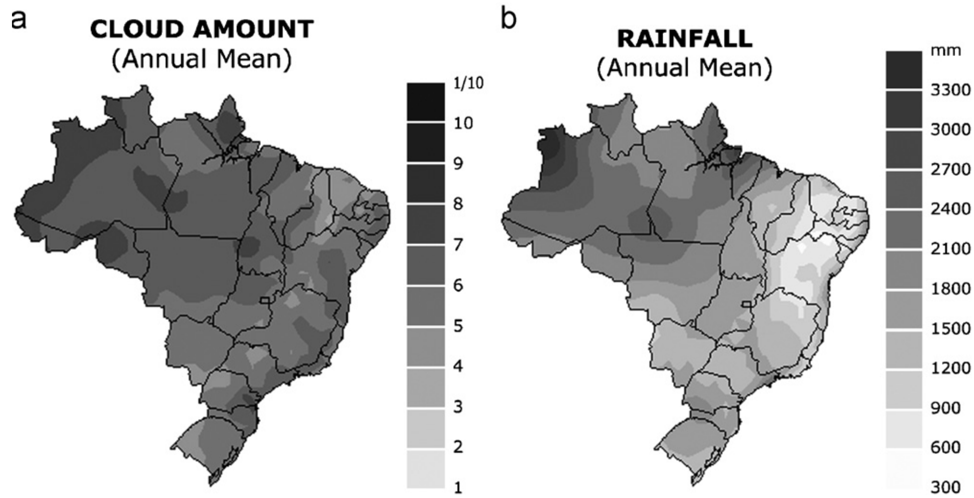

Fig. 4. Maps for annual precipitation and nebulosity in the Brazilian territory based in ground data collected in a 60-year period (1931–1990). *Source*: Brazilian Institute for Meteorology (INMET, 2007).

irradiation for day d of year y from its annual mean in the same year. I_d stands for the mean daily solar flux for the same day d in the time period from 1995 to 2005. $V_{d,y}$ can be understood as the mean value of the ratio between SD_d and I_d.

$$V_{annual} = \frac{V_{d,y}}{N_d} = \frac{\sum_{d=1}^{365}[SD_d/I_d]}{N_d}$$

where

$$SD_d = \sqrt{\frac{\sum_{y=1995}^{2005}(I_{d,y} - I_y)^2}{N_y}} \text{ and } I_d = \frac{\sum_{y=1995}^{2005} I_{d,y}}{Ny} \quad (2)$$

The seasonal variability, $V_{seasonal}$, was defined as the mean intra-seasonal variability, $V_{sea,y}$, observed for each year in the 1995–2005 period. The intra-seasonal variability, $V_{sea,y}$ for a specific year was determined through the ratio between the mean quadratic deviation, $SD_{sea,y}$, and the mean value of the daily solar flux for a specific season, $I_{sea,y}$, as presented in Eq. (3):

$$V_{seasonal} = \frac{\sum_{y=1995}^{2005} V_{sea,y}}{N_y}$$

where

$$V_{sea,y} = \frac{SD_{sea,y}}{I_{sea,y}}$$

$$SD_{sea,y} = \sqrt{\frac{\sum_{d=n1}^{n2}(I_{d,y} - I_{sea,y})^2}{N_{d,sea}}} \text{ and } I_{sea,y} = \frac{\sum_{d=n1}^{n2} I_{d,sea}}{N_{d,sea}} \quad (3)$$

Analyzing the annual variability map, one may notice that the entire Amazon and the Central regions including the western portion of the Northeastern region show lower variability throughout the year—less than 25%. These regions show distinctive climate characteristics that reduce the solar flux variability throughout the year as for example the low nebulosity all through the year in the semi-arid region and the high nebulosity during the summer in the Amazon region.

It can be verified that the seasonal variability shows the same pattern observed for the annual variability. The entire Central–-North area of the country—the Amazon, the Cerrado area, the semi-arid region in Brazilian Northeast and the western part of the Southeast region—show the smallest seasonal variability. The variability is lower during the winter (June through August) and larger in the summer (from December till February). This behavior reflects the nebulosity variation all through the year. During the winter the rain precipitation is low in this entire region and the number of days with clear skies is greater, thereby reducing the variability of solar irradiation in the region. The presence of large nebulosity during the summer explains the larger variability of solar irradiation within this period.

On the other hand, the Southern and coastal area of Southeastern regions presents higher annual variability, around 45%, due to the incursions of cold fronts originating from the deep cyclonic systems in the Antarctic region, mainly in fall and winter seasons. The coastal regions of the South and Southeast show the largest variability during all seasons of the year.

Fig. 6 allows a comparison of the inter-annual variability of the annual and seasonal averages of daily global solar irradiation for each of the Brazilian political regions. The central squares represent the averages in the 10-year period, the outer larger squares represents the range for confidence level equal to 67% (one standard deviation) and the vertical bars show the limits for confidence level of 95%.

In the box plot presented in Fig. 6(a), it can be noted that the Northeast region presented the smallest inter-annual variability (between 5.7 and 6.1 kWh/m^2/day) followed by the North region (between 5.2 and 5.8 kWh/m^2/day). During the 10-year period analyzed, the South region showed larger inter-annual variability with annual mean solar flux varying between 4.6 and 5.6 kWh/m^2/day.

From box plots presented in Fig. 6(b) to (e), one can observe that the Southern region also presents the largest seasonal variability. It is worth noting that the mean solar radiation flux in summer is about 65% larger than it is in winter in this region.

The North region presented the lowest seasonal variability all through the year with the minimum variability in the spring (from 5.7 till 6.1 kWh/m^2/day) and the maximum at the winter (from 4.8 till 6.0 kWh/m^2/day).

The fall and winter seasons showed the largest inter-annual variability in all regions of Brazil (larger spreading measured by the distance between bars on the figure). The frontal systems are supposed to be the main reason for this larger variability in the South and Southeastern regions. The increase in nebulosity resulting from the incursion of frontal systems causes a noticeable reduction of solar irradiation during several consecutive days. The reason for the variability increase observed during the fall and winter seasons in the North and Midwest regions is not clear. A larger quantity of clear sky days can be observed (less nebulosity) in these regions during the dry season (fall and

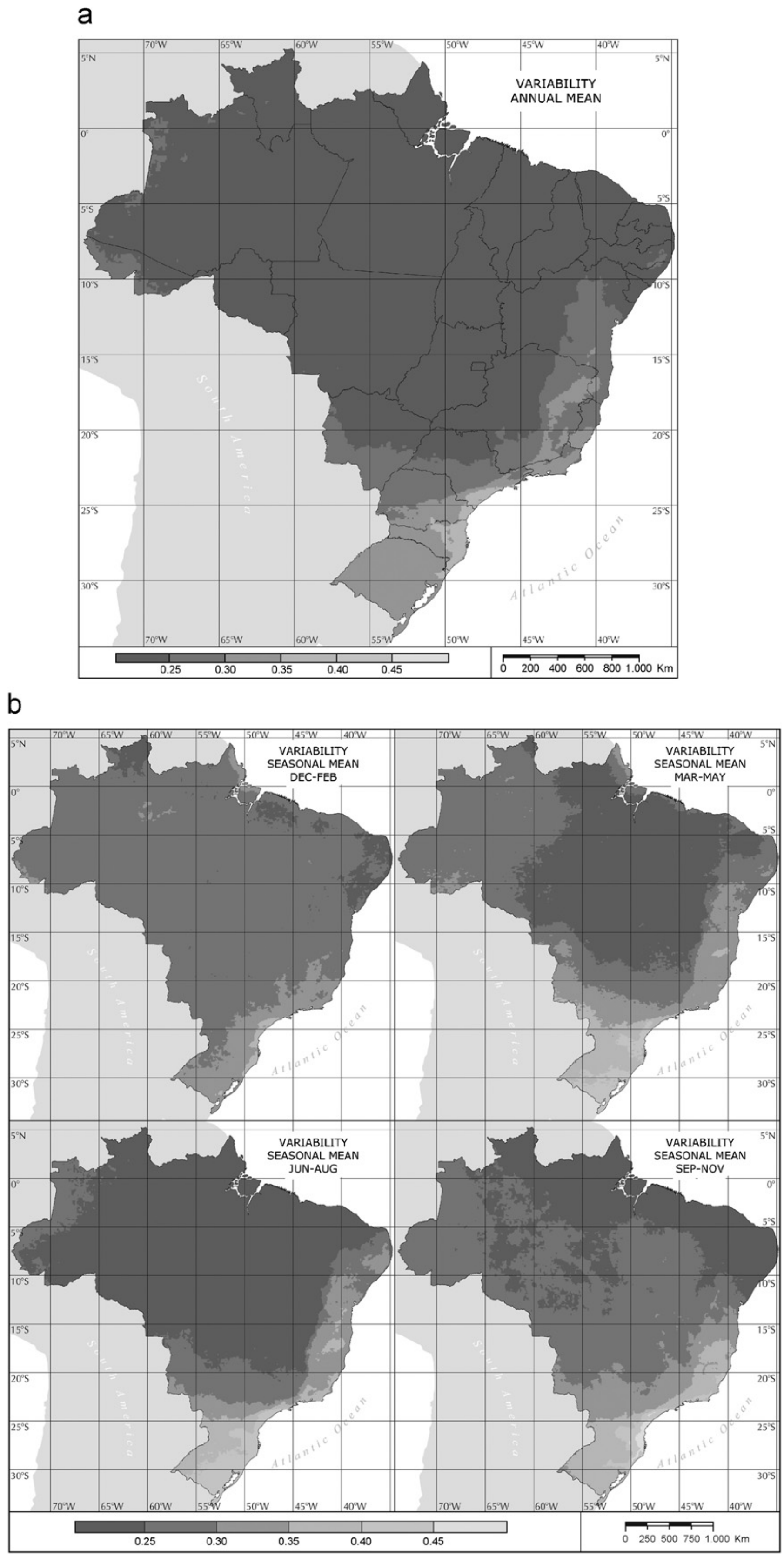

Fig. 5. Maps for annual and seasonal variability of daily totals of global irradiation in the 1995–2005 time interval.

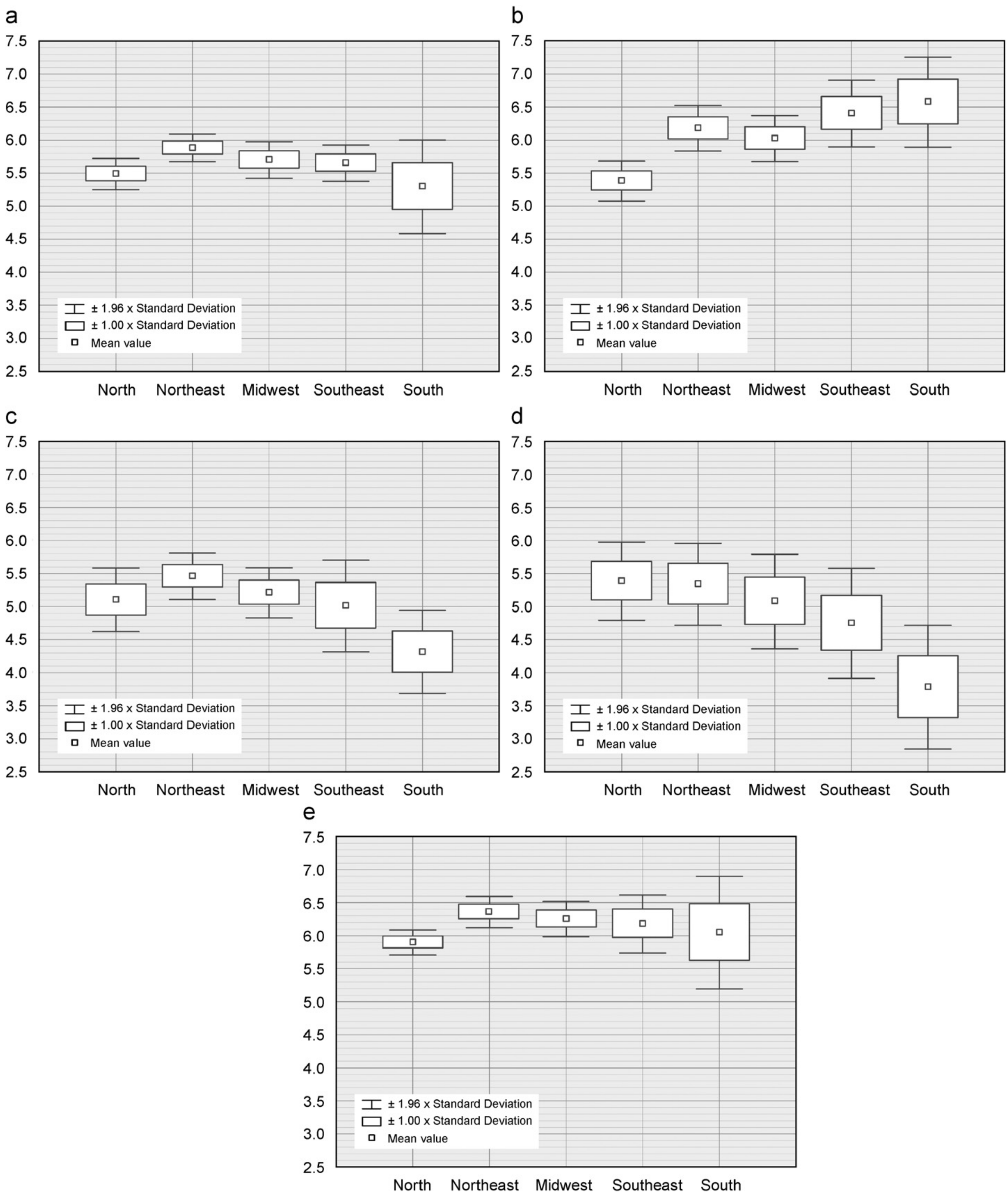

Fig. 6. Variability of annual and seasonal mean values of daily solar irradiation for each of the geographical regions of Brazil: (a) annual, (b) summer, (c) fall, (d) winter and (e) spring.

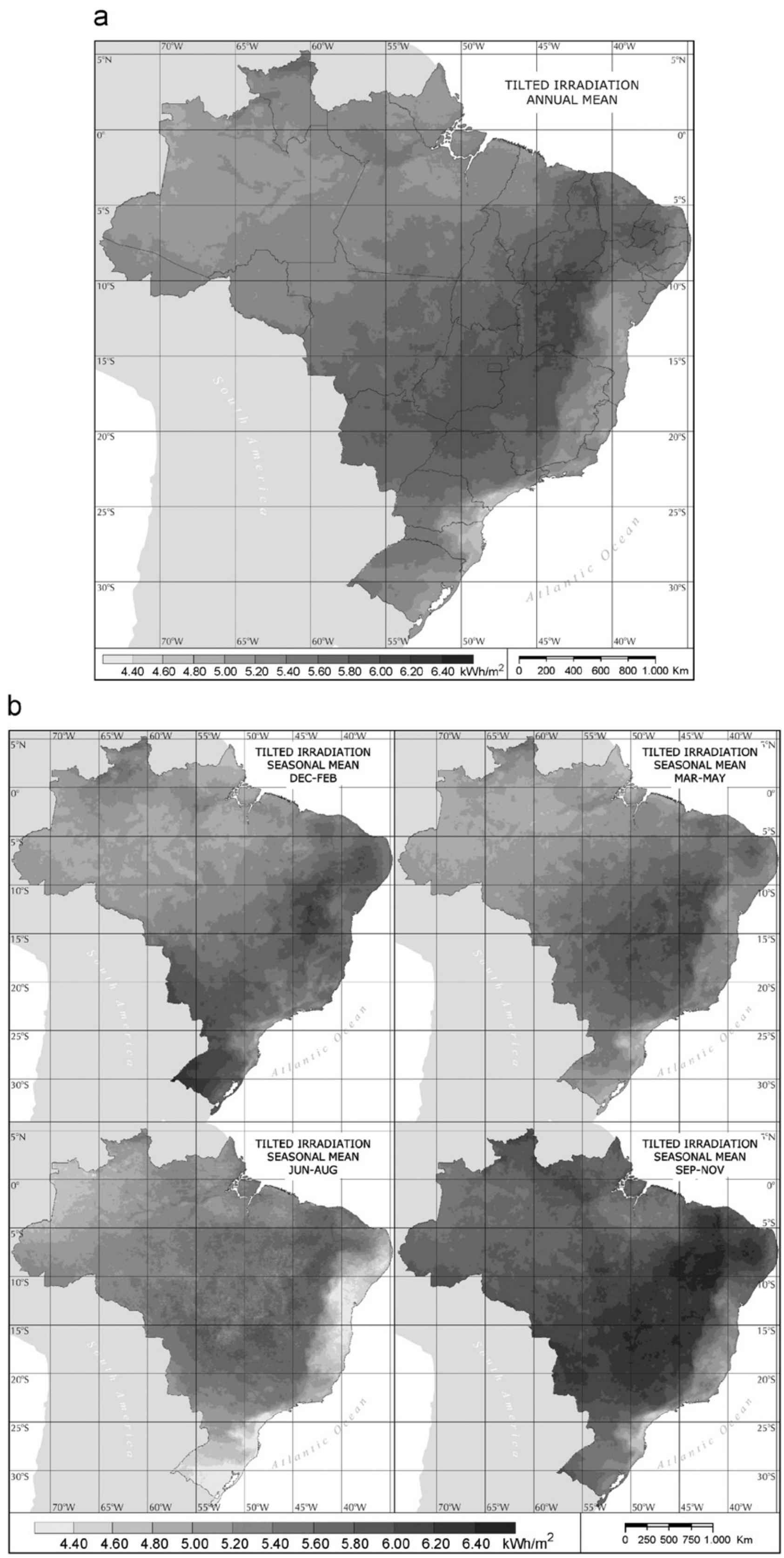

Fig. 7. (a) Annual average of daily sum of the global irradiation on a plane tilted to an angle equals to local latitude. (b) Seasonal averages of daily sum of global irradiation the latitude tilted plane. The seasons are arranged as described in Fig. 3.

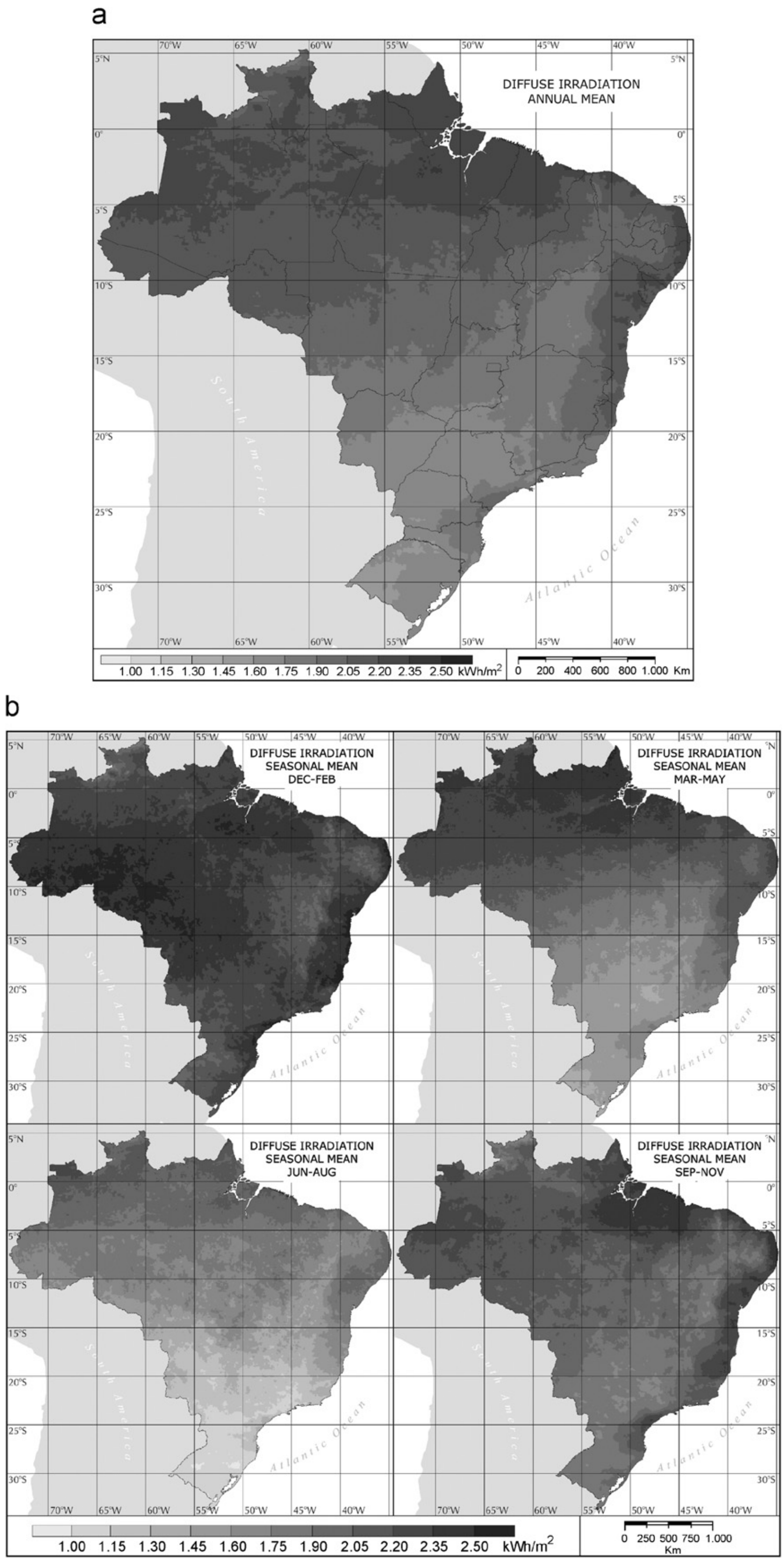

Fig. 8. (a) Annual average of daily sum of the diffuse solar irradiation in Brazilian territory. (b) Seasonal averages of daily sum of the diffuse irradiation in Brazilian territory. The seasons are arranged as described in Fig. 3.

winter). One hypothesis may be the increase of aerosol particle number concentrations emitted to the atmosphere by the burning of biomass typical during this time of the year in these regions.

3.3. Solar irradiation over a tilted plan

Fig. 7 presents the maps for annual and seasonal means of global solar irradiation over a plan tilted to an angle equal to the cell latitude. The assessment of the "tilted" component is very important information for the development of PV applications and solar heating systems. Disregarding the local topography, the solar irradiation over a surface tilted to a latitude angle is the configuration that allows capturing the maximum solar energy throughout 1 year.

All maps in Fig. 7 present similar patterns as discussed for global solar irradiation. The furthermost levels of irradiation on the tilted plane occur in the range that goes from the Northeast to the Southwest during the spring and the smallest values in all Brazilian regions occur during the winter months.

3.4. Diffuse solar irradiation

Fig. 8 exhibits the maps for annual and seasonal averages of the daily total of diffuse solar irradiation. On the annual average one can observe that the Northern region receives greater diffuse irradiation mainly in the estuary of the Amazon River. This is due to the larger nebulosity in the region as a result of the ITCZ influence. Seasonally the greatest diffuse irradiation occurs during the summer throughout the Amazon region. The smallest values happen during the dry season (fall and winter) in the South-eastern and Southern regions.

4. Conclusions

This paper describes the satellite-derived assessment of solar energy resource prepared during the SWERA project. The project SWERA had financial support from UNEP and GEF and it aimed at providing reliable and high-quality information to decision makers, politicians, investors and stakeholders in order to foster clean energy applications in developing countries. The solar irradiation maps for Brazil were prepared by using a radiative transfer model BRASIL-SR fed by climate data and satellite-derived cloud cover data. The reliability of solar resource estimates and model BRASIL-SR performance were checked out through comparisons with solar estimates provided by numerical models adopted in SWERA to map solar resources in other participating countries and comparison with ground data acquired in all Brazilian regions. Concisely, the model BRASIL-SR presented a similar performance as other core models adopted by the SWERA project for solar assessment in other regions, but it usually overestimates solar irradiation—MBE around 6% and RMSE about 13%.

The larger values of global solar irradiation were found for the semi-arid area in the Brazilian Northeast region. The extremely dry environment (semi-desertic) and the high number of sunshine hours all year round resulted in mean solar irradiation around 6.5 kWh/m^2day. Slight smaller values were obtained for the Southern region during spring and summer seasons. However, the solar irradiation there presents higher variability through the year due to the incursions of cold fronts originating from the deep cyclonic systems in the Antarctic region, mainly during fall and winter seasons.

The maps for solar irradiation over a plane tilted in a angle equal to the local latitude point toward the great potential available for solar energy applications in Brazil, even in the semi-temperate climate in the Southern region where annual mean of solar irradiation is comparable to that estimated for the equatorial Amazonian region. It was also verified that all Brazilian territories receive larger solar irradiance than many of the European countries where a large number of solar energy projects are being implemented mainly as a result of good energy regulation for renewables and valuable government incentives.

The scenarios for solar thermal and PV applications, prepared by using the GIS database acquired during SWERA together with the solar resource maps presented here, will be discussed in two other papers to be published in the near future.

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