Available online at www.sciencedirect.com
ScienceDirect
Solar Energy 81 (2007) 517–528
SOLAR ENERGY
www.elsevier.com/locate/solener

Satellite-derived solar resource maps for Brazil under SWERA project

F.R. Martins [a,*], E.B. Pereira [a], S.L. Abreu [b]

[a] *Centre for Weather Forecast and Climate Studies, Brazilian Institute for Space Research, CPTEC-INPE, P.O. Box 515, São José dos Campos 12245-970, Brazil*

[b] *Solar Energy Laboratory, University of Santa Catarina, LABSOLAR-UFSC, Campus Universitário Trindade, Florianópolis 88040-900, Brazil*

Received 4 August 2005; received in revised form 7 July 2006; accepted 14 July 2006
Available online 14 September 2006

Communicated by: Associate Editor Pierre Ineichen

Abstract

The SWERA project is an international project financed by GEF/UNEP which aims at providing a consistent and easily accessible database to foster the insertion of renewable energies on the energy matrix of selected pilot countries. In Brazil, the project is now at the stage of formatting information, validating of solar and wind resource assessment models, and ancillary GIS data integration. Solar energy resource maps in Brazil were generated using the satellite radiation model BRASIL-SR and the NREL's CSR (climatological solar radiation) model. This paper describes the methodology used to produce the solar maps using the BRASIL-SR radiation model and discusses the seasonal and yearly means of daily solar irradiation maps obtained for 1995–2002 period.

Keywords: Solar energy; Solar irradiance maps; Radiative transfer model; Ground truth data

1. Introduction

Modern lifestyles demand a continuous and reliable supply of energy. The human development is strongly related with the per capita consumption of energy and, as a consequence of improvement of the life quality in the developing countries, it is expected an annual growth of the energy demand of 4% in those countries (Goldemberg, 1998).

It is possible to establish a cause/effect relation linking energy use and development with environmental damage as it has been demonstrated by many researches. The third IPCC report (IPCC, 2001) confirmed that the Earth's climate is changing as a result of human activities, mainly due to fossil fuel energy use. The IPCC report stated that alternative energy sources should be implemented over the next 20 years to help reduce greenhouse gas emissions (Sims, 2004). The increase in energy demand, the high prices of conventional fuels, the political crises in producing areas of fossil fuels, and the growing concern with the preservation of the environment have stimulated the scientific survey for alternative energy resources.

Significant business opportunities will result from near term potential for renewable energy and related new industries. However, the mid and long term energy planning requires reliable information on many natural resources focusing the renewable energy policy. Usually investors, risk capital enterprises, and independent energy producers are not aware of the available renewable energy options. Besides that, potential investors tend to avoid the risk of activities dealing with the development of renewable energy projects where reliable and sufficiently detailed data are non existent. In summary, the main barriers to investments in renewable energy production in developing countries are:

(a) the lack of reliable assessment of in-country renewable energy resource potentials,

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

0038-092X/$ - see front matter
doi:10.1016/j.solener.2006.07.009

(b) the lack of long time series of ground data with adequate space distribution for studies of uncertainties and time trends,
(c) the limited knowledge of the variability and confidence levels linked to several natural and non-natural variables such as climate, topography and man-made impacts in environment.

The Centre for Weather Forecast and Climatic Studies of Brazilian Institute for Space Research (CPTEC/INPE) is coordinating the Brazilian component of SWERA project. SWERA (Solar and Wind Energy Resource Assessment) is a project financed by United Nations Environment Programme (UNEP), with co-financing by Global Environmental Facility (GEF) in the area of renewable energies, more specifically, solar and wind energy. The SWERA project is assembling high quality information on solar and wind energy resources into consistent GIS (geographic information system) analysis tools. The project is mainly intended for the public and private sectors involved in the development of the energy market and it shall enable policy makers to assess the technical, economic, and environmental potential for large-scale investments in renewable and sustainable technologies.

2. SWERA project

The Solar and Wind Resource Assessment (SWERA) project aims at fostering the insertion of renewable energies on the energy matrix of developing countries. There are thirteen countries involved in the project and they are divided into three great regional groups: Africa, Latin America, and Asia. In Latin America there are six countries participating in the leading phase of the project: Brazil, Cuba, El Salvador, Guatemala, Honduras, Nicaragua and Belize. More details on general goals and main results for other countries can be found at <http://swera.unep.net/>.

The Brazilian Institute for Space Research (INPE) is coordinating the SWERA activities in Brazil. The Solar Energy Laboratory of University of Santa Catarina (LABSOLAR/UFSC), the Brazilian Center of Wind Energy (CBEE), Brazilian Centre for Research in Electricity (CEPEL) and the US Renewable Energy Laboratory (NREL) are partnership this enterprise.

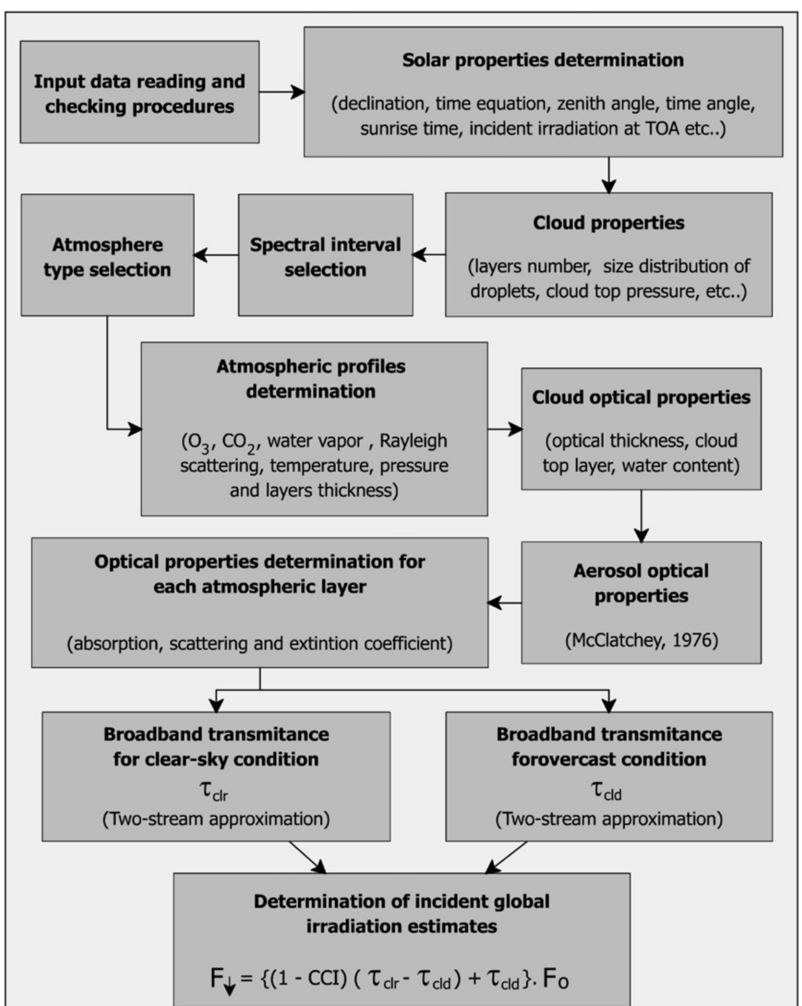

Fig. 1. Schematic diagram of radiative transfer model BRASIL-SR.

The Geospatial toolkit for Brazil, which is being developed by NREL and implemented by CPTEC, will be one of the chief SWERA products and it will put together 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, power plants (nuclear, hydroelectric and others), along with the solar and wind energy resources information for the Brazilian territory. The toolkit uses ArcObjects, a map-based software application that can be used for decision making and policy analysis as well as identifying potential areas for wind and solar energy projects. The GIS toolkit aims at to providing the government and the private investor with an uncomplicated 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.

3. Solar energy resource maps

Three methods for solar resource assessment are being used in Brazil under the SWERA project. The first one is based on the information available through the "US National Aeronautics and Space Administration's (NASA's) Surface Solar Energy (SSE) Low Resolution" (100 km) global solar energy data set (<http://eos-web.larc.nasa.gov/sse/>). The second method is based on the climatic information and has been developed by the NREL (USA). The technique uses the 40 km medium-resolution gridded cloud cover data (Real-Time Nephanalysis – 1985–1991) provided by the US National Climatic Data Center (NCDC) as input to NREL's Climatological Solar Radiation (CSR) model (Maxwell et al., 1998). The model outputs monthly and annual average of daily total solar resource values for fixed flat plate collectors oriented at latitude tilt (for photovoltaic systems), direct normal values (for concentrators) and diffuse sky values (for day lighting analysis).

The last method is a satellite-derived radiative transfer model, BRASIL-SR, developed by CPTEC/INPE and LABSOLAR/UFSC (Martins, 2001; Pereira et al., 2000) based on GKSS model described in Stuhlmann et al. (1990). The maps produced using model BRASIL-SR will be presented and discussed in its details in this paper.

3.1. Model BRASIL-SR

The model BRASIL-SR provides solar irradiation maps using the "Two-Stream" approach to solve atmospheric radiative transfer equation, the GOES-EAST satellite images and a climate database which includes temperature, surface albedo, relative humidity and visibility data (Martins and Pereira, 2006; Pereira et al., 2000).

Fig. 1 presents a schematic diagram of model BRASIL-SR. The estimates for surface solar irradiation, $F_{\downarrow}$, are obtained from Eq. (1) where F_0 is the extraterrestrial solar irradiation. The first term is associated with clear sky condition, and the second one is related with overcast condition. The clear (τ_{clear}) and cloudy (τ_{cloud}) transmittances are obtained from atmospheric parameterization using climatic data (temperature, relative humidity, surface albedo, visibility and cloud properties) and geographical position (latitude, longitude and altitude). The effective cloud cover coefficient, CCI, is a weighting function for the linear relation between clear and overcast sky conditions. In spite of being a quite simple approach, Eq. (1) presents very good results as demonstrated by Colle and Pereira (1998):

$$F_{\downarrow} = F_0\{\tau_{\text{clear}}(1 - \text{CCI}) + \tau_{\text{cloud}}\text{CCI}\}. \quad (1)$$

The confidence and reliability of the CCI is a chief factor to get solar estimates with good accuracy. The CCI value contains information about spatial distribution and optical thickness of clouds and it is obtained as described in Eq.

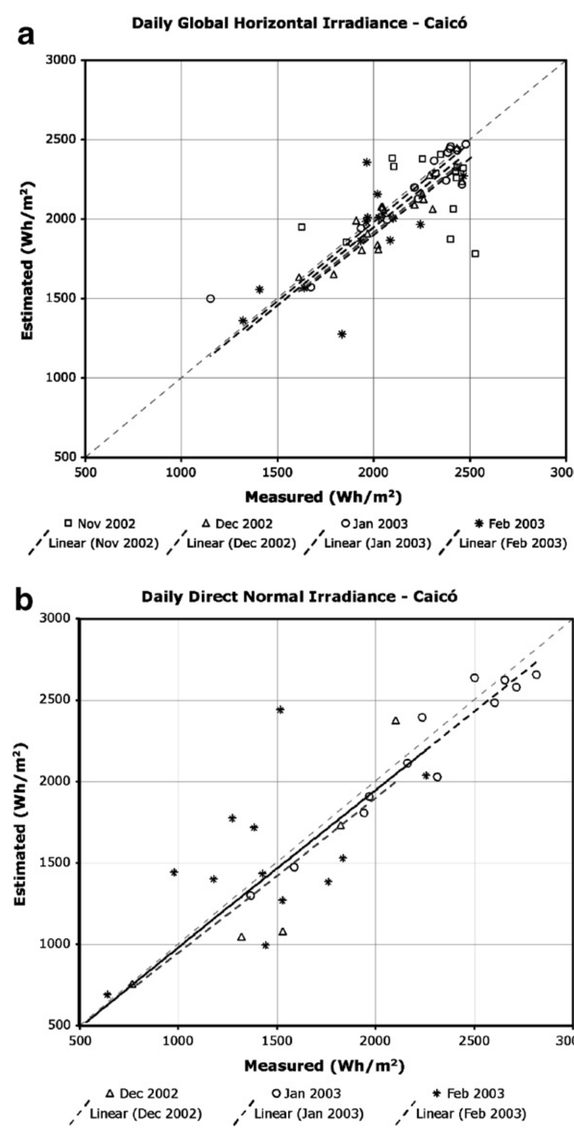

Fig. 2. (a) Comparison among estimated and measured global irradiance at Caicó/PE. (b) Comparison among estimated and measured direct normal solar irradiance for the same location.

(2), where L is the visible radiance measured by the satellite sensor, and L_{clear} and L_{cloud} are, respectively, the visible radiances measured in the same wavelength spectral range at clear and overcast sky conditions. The L_{clear} and L_{cloud} values for each image pixel are produced by statistical analysis of satellite images (Martins et al., 2003):

$$\mathrm{CCI} = \frac{[L - L_{\mathrm{clear}}]}{[L_{\mathrm{cloud}} - L_{\mathrm{clear}}]}. \tag{2}$$

The methodology used to estimate direct beam irradiance (DNI) assumes that cloud cover contribution to the direct transmittance can be added to the clear sky direct

Table 1
SONDA sites chosen to provide ground data to the validation step of the BRASIL-SR solar estimates

ID	Site	Location	Description
1	Balbina	01°55′S 59°26′W 230 m	Located in Amazon Region. Wet climate and larger precipitation. Influence of biomass burning events in May–October period
2	Ouro Preto d'Oeste	10°52′S 61°58′W 200 m	Located in Amazon Region. Wet climate and larger precipitation. Influence of biomass burning events in May–October period
3	Caicó	06°28′S 37°05′W 176 m	Located in the Northeast of Brazil. Arid climate and large number of clear sky days
4	Petrolina	09°04′S 40°19′W 387 m	Located in the Northeast of Brazil. Arid climate and large number of clear sky days
5	Brasília	15°36′S 47°43′W 1023 m	Located in the central region of Brazil (Cerrado region). Influence of biomass burning events in May–October period
6	Cuiabá	15°33′S 56°04′W 185 m	Located in the central region of Brazil (Cerrado region). Influence of biomass burning events in May–October period
7	Florianópolis	27°34′S 48°32′W 12 m	Medium size coastal city in South region of Brazil. Influence of cold fronts originated in Antarctica. Seasonal signal is very important influence to the solar energy resource
8	São Martinho do Sul	01°55′S 59°26′W 230 m	Located in very South of Brazil. Influence of cold fronts originated in Antarctica. Seasonal signal is very important influence to the solar energy resource

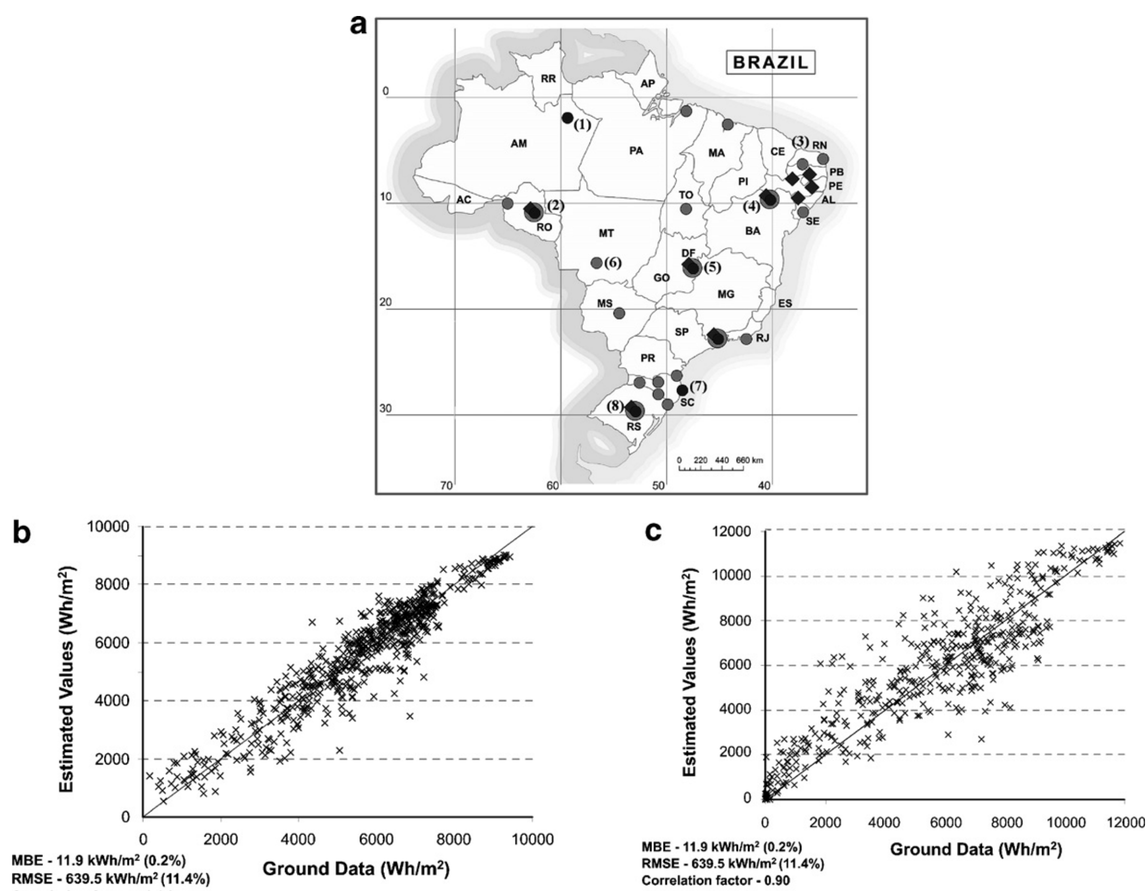

Fig. 3. (a) Location of the SONDA measurement sites. The numbered sites were employed in the validation step of solar estimates provided by BRASIL-SR. Table 1 describes each numbered site. (b) Comparison among measured and estimated values of global solar irradiation. (c) Comparison among measured and estimated values of direct beam solar irradiation. MBE stands for mean bias error and RMSE denotes root mean square error.

transmittance ($\tau_{\text{atm-dir}}$) due to aerosols, water vapor and atmospheric gases. Therefore, the direct solar estimate is calculated from the following equation:

$$\text{DNI} = F_0 \cdot \tau_{\text{atm-dir}} \cdot \tau_{\text{cloud-dir}}, \quad (3)$$

where $\tau_{\text{cloud-dir}}$ represents the cloud transmittance for direct component of solar irradiation. The $\tau_{\text{clear-dir}}$ is obtained using the "two-stream" technique for clear sky condition and $\tau_{\text{cloud-dir}}$ is estimated from cloud cover index, CCI, using the following approach (Stuhlmann et al., 1990):

$$\tau_{\text{cloud-dir}} = (1 - \tau_c)/(\beta - \tau_c) \quad (4)$$

where

$$\begin{cases} \tau_c = (\text{CCI} + 0.05) & \text{if CCI} < 0.95, \\ \tau_c = 1.0 & \text{if CCI} \geqslant 0.95. \end{cases}$$

The quality and reliability of solar estimates provided by BRASIL-SR model were checked out in two steps: (a) an inter-comparison task of radiative transfer models used in SWERA project to produce solar maps for Central America, Africa and Asia and (b) comparison with high quality ground data acquired in several sites in the Brazilian territory.

In the first step, the performance of the BRASIL-SR, the DLR's direct normal irradiation model, the CSR (NREL) and the modified Kasten model from SUNY-ALBANY were compared to each other. For this task, the ground data were provided by the SWERA radiation test site located at Caicó (06°28′01″S–037°05′05″W, 176 m), plus the BSRN sites of Balbina (1°55′07″S–59°25′59″W, 230 m) and Florianópolis (27°34′18″S–048°31′42″W, 12 m). These three sites were chosen due to the high quality data provided and their location in the major climatic regions of Brazilian territory. The Caicó site was implemented in the Northeast of Brazil by the SWERA project to provide high quality ground data where a large number of clear sky days occur in reason of arid climate observed all along the year. The Balbina site is located in the Brazilian Amazon region which is characterized by wet climate and larger precipitation all along the year. Florianópolis site is located in a medium size coastal city in South region of Brazil where two seasons are well defined: dry season (from April to September) and wet season (from October to March). Fig. 2 presents the plots of estimated versus measured values of global and direct normal solar irradiation obtained for Caicó. Similar results were obtained for the other two sites and more details about the intercomparison task of SWERA project can be retrieved in Martins (2003) and Beyer et al. (2004).

The validation step of model estimates are being conducted by using eight ground sites described in Table 1. Five sites started to collect data in August/2004 as part of SONDA network (Ouro Preto d'Oeste, Petrolina, Brasilia, Cuiabá and São Martinho do Sul). The other three sites already operated and had started to be part of SONDA network in August/2004. SONDA project (Brazilian Management System of Environmental Data for the energy sector) is a national initiative coordinated by CPTEC/INPE and supported by Brazilian Financing Agency for Research and Projects (FINEP). Its main objective is to provide the country with a network of high quality, reliable and

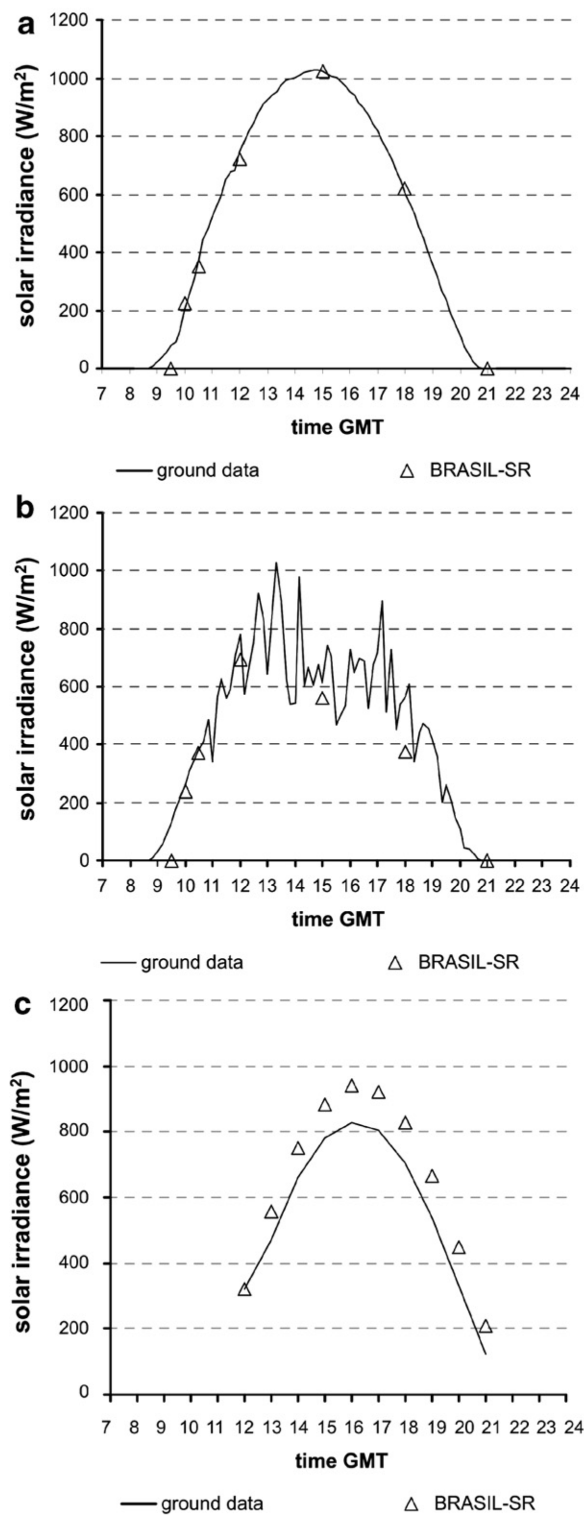

Fig. 4. Plots of daily cycle of global solar irradiation for (a) clear sky day in Petrolina; (b) overcast day in Petrolina and (c) clear sky day in Cuibá. Continuous line represents the ground data and triangles are the estimated values provided by BRASIL-SR model at the GOES-12 image times.

integrated ground data acquisition sites for ground-truth in models and satellite-derived assessment of solar and wind energy (Martins et al., 2005). Fig. 3(a) presents a location map of ground measurements sites. More details about sites location and measured data of the SONDA network can be found in the website: <www.cptec.inpe.br/sonda/>.

Fig. 3 presents the results of the validation step of BRASIL-SR using ground data acquired in 2004/2005. The scattering plot presented in Fig. 3(b) compare estimated and measured values of global daily solar irradiation. It can be noted that estimated values provided by the BRASIL-SR model for global irradiation are in good agreement with ground truth data: low mean bias error (MBE equals to 0.2% of the mean global solar irradiation) and root mean square error (RMSE equals to 11.4% of the mean global solar irradiation). In spite of that, it is expected that

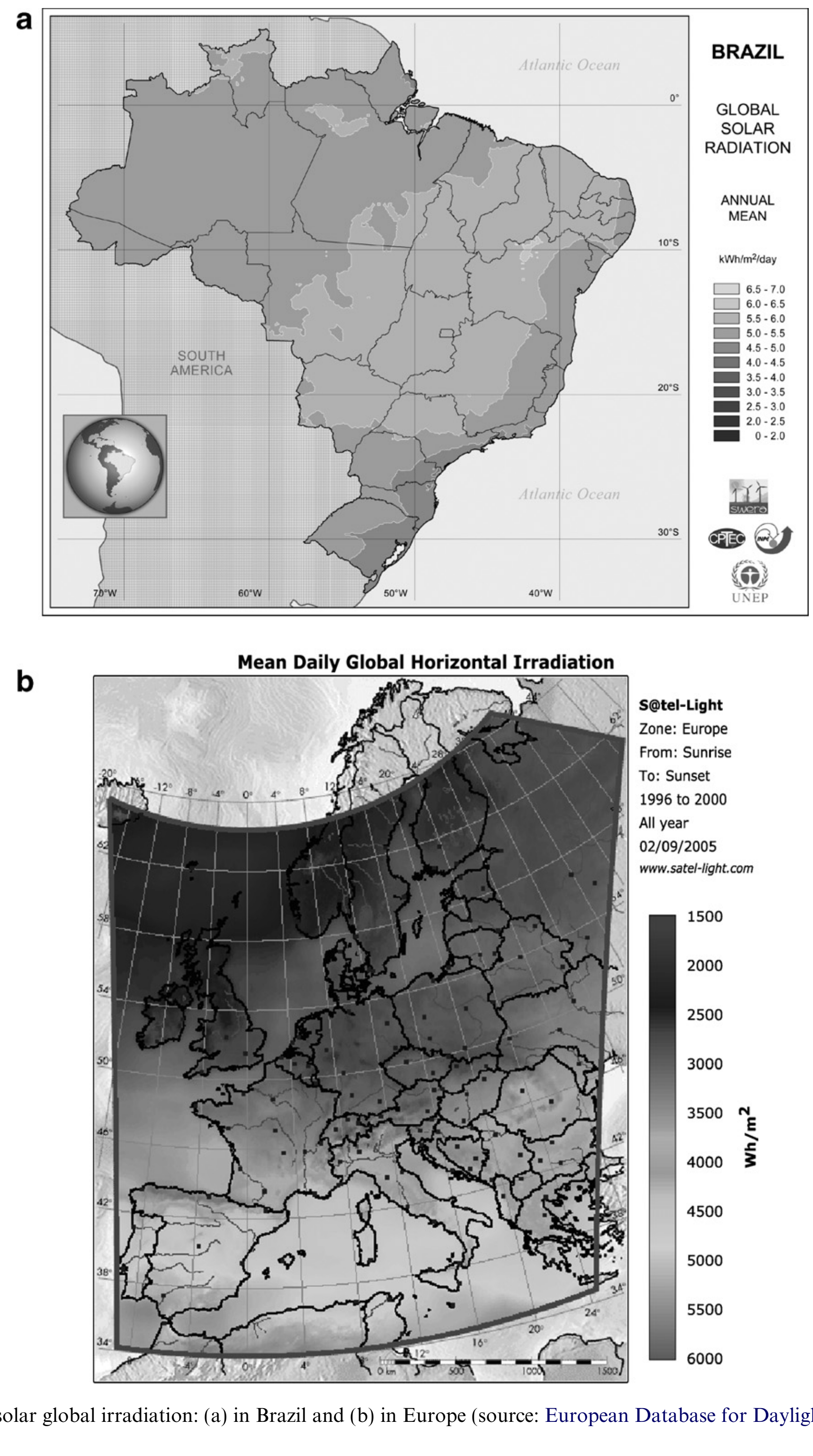

Fig. 5. Annual mean daily solar global irradiation: (a) in Brazil and (b) in Europe (source: European Database for Daylight and Solar Radiation, 2005).

mean deviations (MBE) were larger in the Amazon and central area of Brazil due to biomass burning aerosol emitted in dry season (May–October) not took into account by BRASIL-SR model (Martins and Pereira, 2006). Fig. 4 presents a case study of daily cycle for Petrolina and Cuiabá. It can be noted that the BRASIL-SR model fits well the daily cycle for global irradiation in clear sky and overcast days in Petrolina. On the other hand, BRASIL-SR overestimates the solar irradiation in Cuiabá in a clear sky day in September due to the larger aerosol optical depth. Cuiabá is in the middle of the Cerrado region where the number of biomass burning events reaches its maximum in September (Pereira et al., 2000).

The BRASIL-SR results for direct beam solar irradiation presented a larger spreading as it can be noted from Fig. 3(c). The direct beam solar irradiation values provided by BRA-

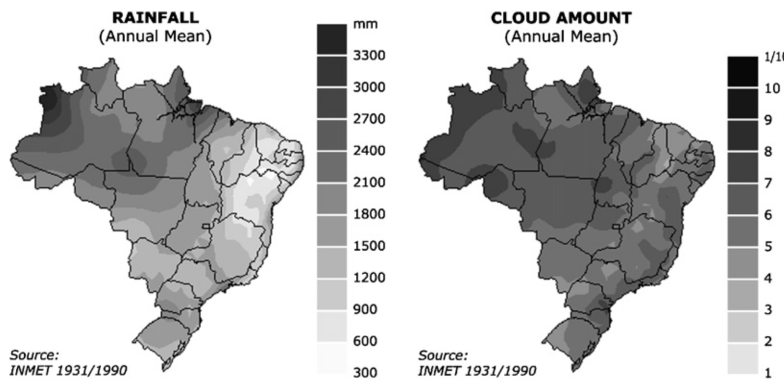

Fig. 6. Annual mean precipitation and cloud cover obtained from ground observations for 1931–1990 (source: INMET, 2004).

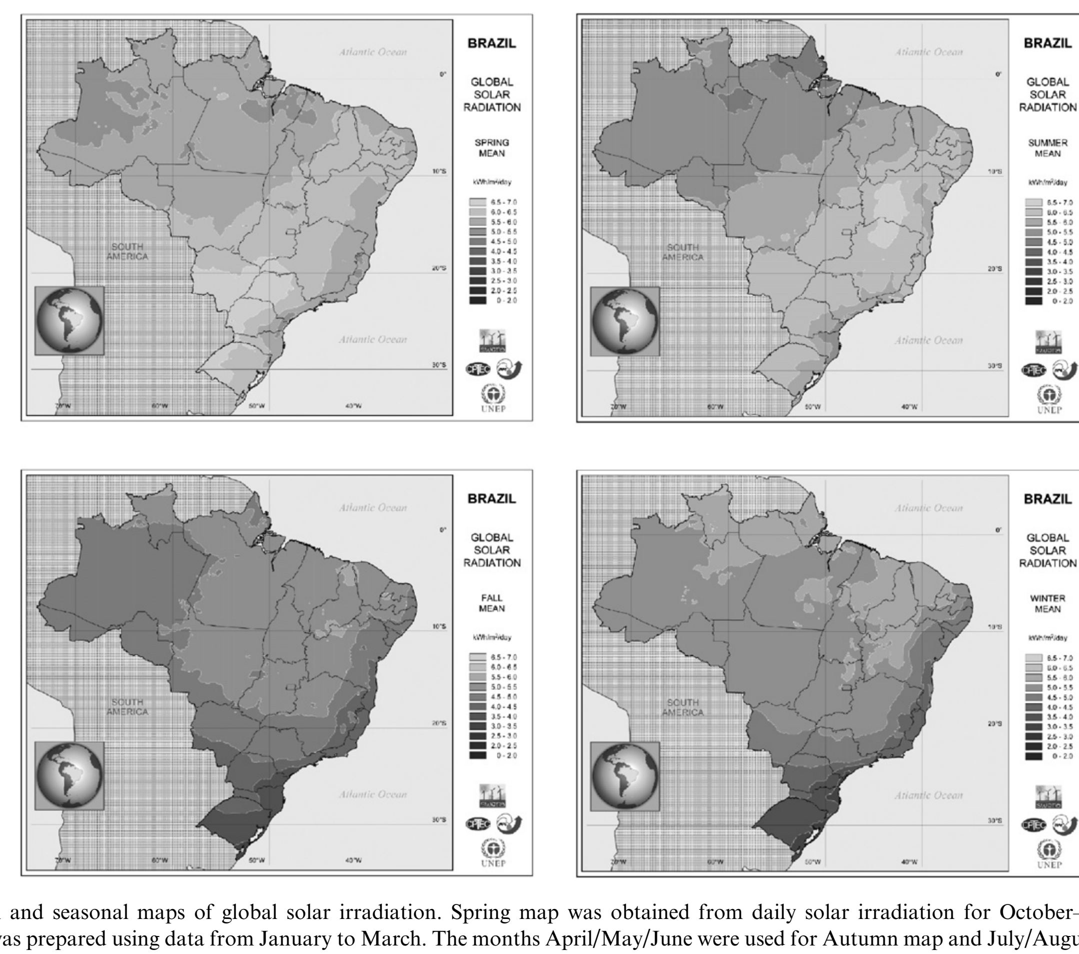

Fig. 7. Annual and seasonal maps of global solar irradiation. Spring map was obtained from daily solar irradiation for October–December period. Summer map was prepared using data from January to March. The months April/May/June were used for Autumn map and July/August/September were employed for Winter map.

SIL-SR overestimated the ground data and presented a larger deviations (MBE = 3.5% and RMSE = 23.9%). The simple parameterization used to model the cloud transmittance of the direct beam ($\tau_{cloud\text{-}dir}$) is responsible for the larger deviations. The BRASIL-SR has underestimated $\tau_{cloud\text{-}dir}$ causing an overestimation of direct beam irradiation, mainly in the overcast days (lower solar irradiation values).

The validation process will continue to include ground data from other SONDA sites and to expand analysis to the entire time period employed to produce annual and seasonal maps of solar irradiation. The main obstacle to complete the validation is the lack of reliable ground data. Only two BSRN (Baseline Solar Radiation Network) were running before 2004 when SONDA network started to collect data: Florianópolis (since 1994) and Balbina (since 1996). The SWERA measurement site located in Caicó started to collect data in November 2002.

3.2. Results

All the maps presented here show average of daily totals of estimated solar irradiation provided by the model BRASIL-SR for the period 1995–2002. Fig. 5(a) presents annual mean of daily global solar irradiance in Brazil. In spite of the large differences in climate characteristics among North and South regions, the annual mean of daily global solar irradiation is relatively homogeneously distributed and only small differences can be observed. The maximum value – more than 6.5 kW h/m^{2}day – occurs in North of the state of Bahia close to the state border with Piauí (around 10°S/43°W). This area presents a semi-arid climate with low precipitation (around 300 mm) and the lowest mean cloud cover of Brazil (INMET, 2004). The minimum value, around 4.25 kW h/m^{2}day, was obtained for Northeast of the Santa Catarina state (around 26°S/49°W), which is characterized by a relatively large average precipitation. Fig. 6 shows the maps for the annual mean of precipitation and cloud cover for Brazil.

Fig. 5 depicts the annual mean for the global solar irradiation in Brazil put side by side with this same information for Europe for comparison (European Database for Daylight and Solar Radiation, 2005). Solar irradiation levels observed in practically all parts of Brazil are higher than those observed for most of the European countries. In spite of the much higher solar resources available in most of Brazil, the number of solar energy projects here are virtually inexistent when compared to the reality in some European countries (e.g., Germany, Spain, and France).

Fig. 7 presents the seasonal mean of global horizontal solar irradiance. It is worth of note that the South region is subjected to larger mean irradiances than the north region during the summer season notwithstanding the latter being much closer to the equator. This is explained by climate characteristics of Amazon region – 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 region 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. The northwest of the Brazilian Amazonian presents large precipitation rates even in the dry season (1100 mm) as a result of ITCZ displacement to the North Hemisphere and incursion of the Trade Wind (Aliseos) from Atlantic Ocean. This climate feature is responsible for the lower solar irradiation in coastal areas of the northern region and in the western area of Brazilian Amazonian.

Fig. 8 shows the variability of solar irradiance for the five geographical regions of Brazilian territory. It can be noted that solar irradiance in South and Southeast regions presents higher variability along the year due to the incursions of cold fronts originated from the deep cyclonic systems in the Antarctic region, mainly during fall and winter seasons.

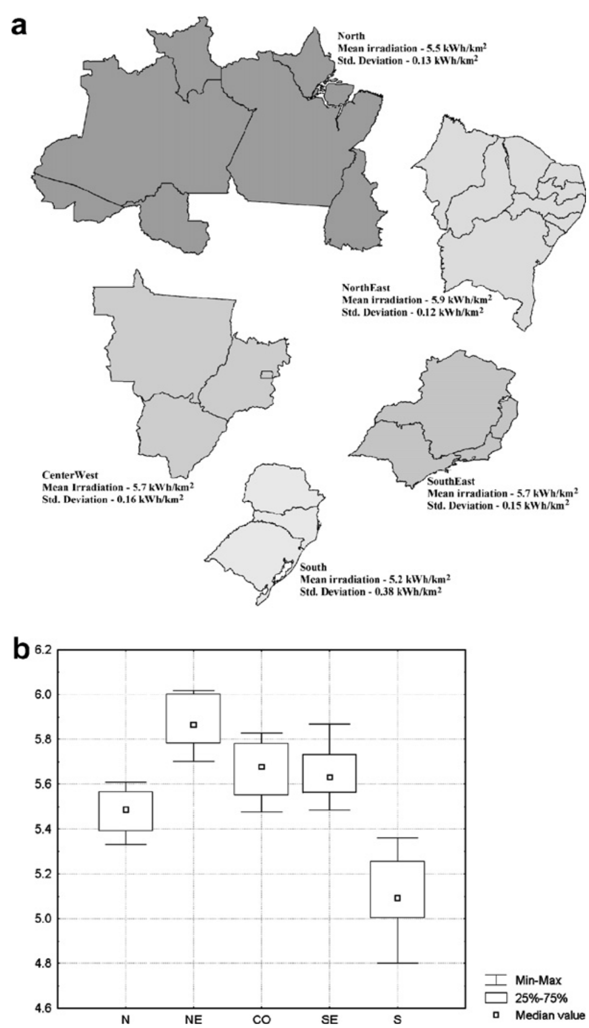

Fig. 8. Annual mean of daily solar energy in each geographical region of Brazil (a) and (b) its variability throughout the year.

Fig. 9 presents the annual mean and seasonal maps for the direct normal component of the solar irradiation. Fig. 10 presents the same maps for global solar irradiances over a tilted plan to an angle equals to the site latitude. The assessment of the "tilted" component is very important information for the development PV (Photovoltaic), while the direct normal is essential for CSP (concentrating solar plants) projects, both for electricity production.

Important information for project designers and investors in renewable energy is obtained by comparing solar (and wind) energy resource maps against geographical, socio-economic, and infrastructure data. This can be easily achievable by using the SWERA GIS toolkit. Fig. 11 shows an example of a simple query output provided by this toolkit. It shows the Brazilian regions with solar irradiation larger than 5.5 kW h/m^2/day and more than 100 km far from paved roads. Such query is an example of what should be considered in decisions and policies for new energy investments. In this particular case the distance from the paved highways is the issue since it could raise the project implementation and operation costs by imposing increased difficulties for the transport of the fossil fuel, for example.

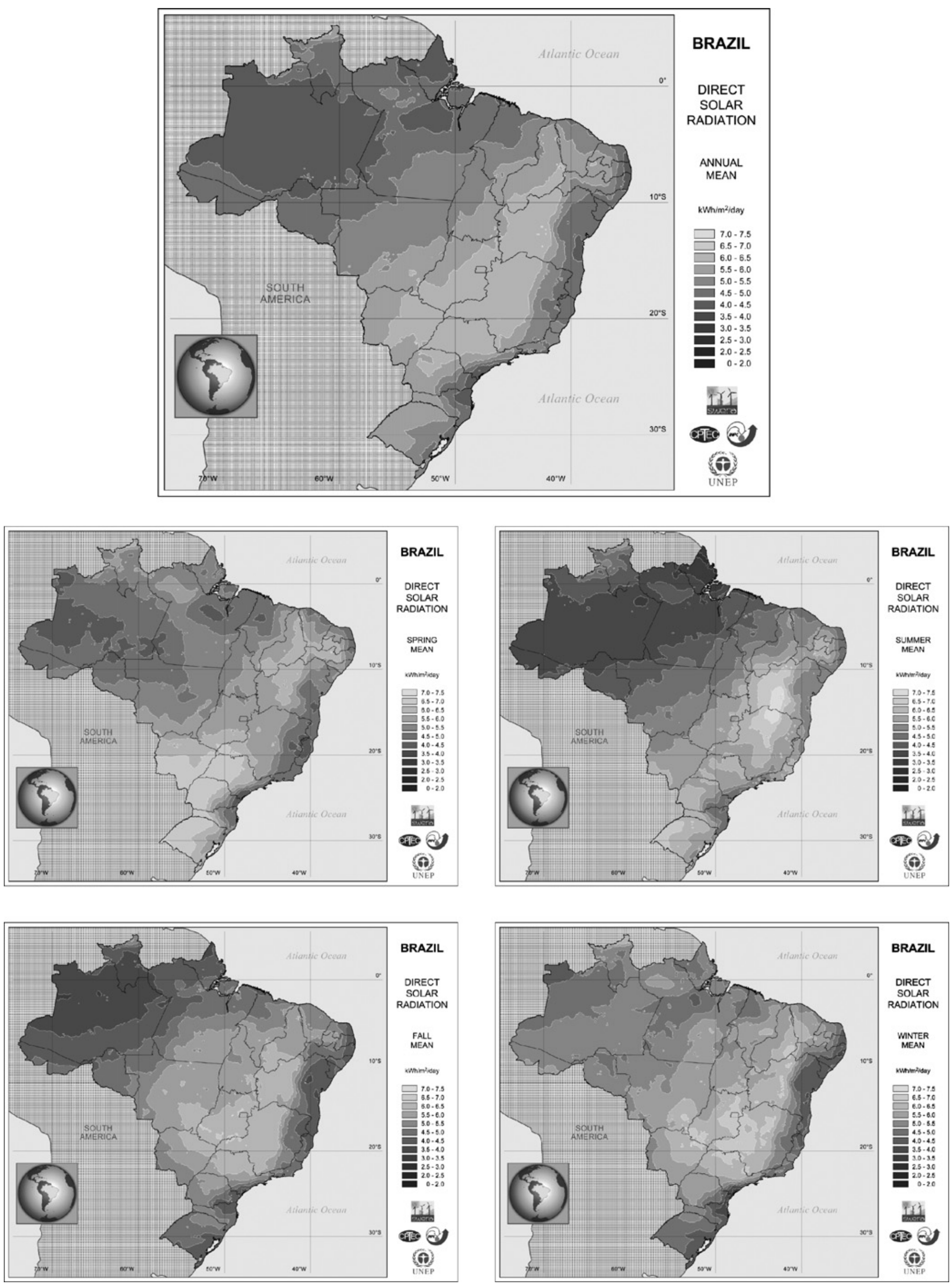

Fig. 9. Annual mean and seasonal maps for direct beam solar irradiation. Seasonal maps were prepared as described in Fig. 7.

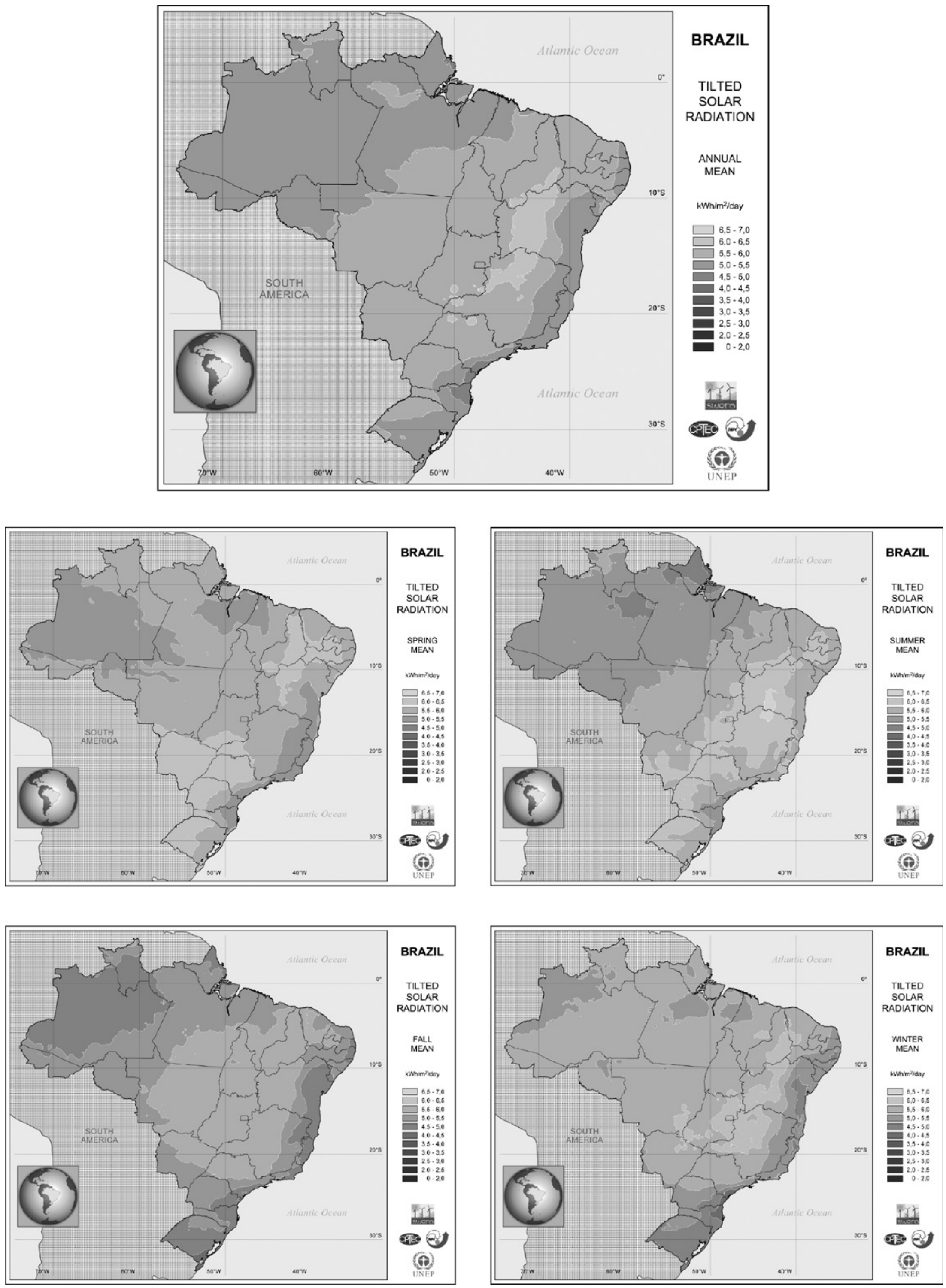

Fig. 10. Annual mean and seasonal maps for direct solar irradiation over a tilted plan. Seasonal maps were prepared as described in Fig. 7.

4. Conclusions

The project SWERA aims at providing reliable and high quality information to decision makers, politicians, investors and stakeholders for facilitating clean energy development in developing countries. CPTEC/INPE and LABSOLAR/UFSC have produced solar irradiance maps for Brazil using climatological data and the BRASIL-SR satellite model. Results from cross-comparisons reviewed the issue of model performance as different radiative transfer models were compared to each other. Besides that, results from comparison among solar irradiance estimates and ground truth data showed that model BRASIL-SR estimates present small deviations assuring the reliability of solar maps.

Fig. 11. Query output showing the Brazilian regions with solar irradiation larger than 5.5 kW h/m^2/day and distant more than 100 km far from roads. Lines inside Brazilian borders represent the major Brazilian roads.

The solar irradiance maps demonstrate the great potential available for exploitation in Brazil, even in the semi-temperate south region where annual mean of solar irradiation is comparable to the estimated in several areas of the equatorial Amazonian region. It was also verified that all Brazilian territory receives higher solar irradiance than in 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 big government incentives.

The larger values of solar irradiance 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 solar irradiation values of the order of 6.5 kW h/m^2 day on the average. Similar values were obtained for the South region during spring and summer seasons. However, the solar irradiance in South region presents higher variability along the year due to the incursions of cold fronts originated from the deep cyclonic systems in the Antarctic region, mainly during fall and winter seasons.

Presently the project is investigating the annual and seasonal variability based on the long time series of solar radiation data compiled during the project's development.

Future work includes the study of the impact of aerosols emitted by induced forest fires on solar maps. This study will possibly improve the confidence levels of the model output by reducing the estimate deviations. Furthermore the improvement of techniques for cloud cover determination in regions where ground is covered by snow will also be addressed. Although snow does not usually occur in Brazil, this study will allow the extension of the method for the rest of South America, mainly in the Andes and Patagonia regions.

Acknowledgements

This work was possible thanks to the financial support of UNEP/GEF (No. GFL-232827214364 – SWERA), FINEP (No. 22.01.0569.00), CNPq (No. 381072/2002-9) and FAPESP (No. 2005/0398-8). This work was prepared with the fundamental contribution of the following colleagues: Silvia V. Pereira, Cristina Yamashita, Sheila A. B. Silva, Hugo J. Corrá, Rafael Chagas, Chou Sin Chan and Raphael Ventura Dutra. The following institutional acknowledgment is due to Centre for Weather Forecast and Climatic Studies (CPTEC) and, in special, for the people from Environmental Satellite Division (CPTEC-DSA) for the continuous support in satellite data and ancillary satellite products. Thanks are due to Sergio Colle from LABSOLAR for rewarding long time collaboration, Dave Renné (NREL/USA), Richard Perez (SUNY/Albany) and Tom Hamlin (UNEP) for helping and scientific contribution on the development of SWERA project.

References

Beyer, H.G., Pereira, E.B., Martins, F.R., Abreu, S.L., Colle, S., Perez, R., Schillings, C., Mannstein, H., Meyer, R., 2004. Assessing satellite derived irradiance information for South America within the UNEP resource assessment project SWERA. In: Proc. of 5th ISES Europe Solar Conference, Freiburg, Germany.

Colle, S., Pereira, E.B., 1998. Atlas de irradiação solar do Brasil (primeira versão para irradiação global derivada de satélite e validada na superfície). INMET, Brasília, Brazil.

European Database for Daylight and Solar Radiation, 2005. Available from: <http://www.satel-light.com>.

Goldemberg, J., 1998. Energia, meio ambiente e desenvolvimento. EDUSP, São Paulo, Brazil.

INMET, 2004. Normais Climatológicas. Available from: <http://www.inmet.gov.br/climatologia/>.

IPCC, 2001. IPCC Climate Change 2001 (3 vols.). United Nations Intergovernmental Panel on Climate Change. Cambridge University Press, UK. Available from: <htpp://www.ipcc.ch>.

Martins, F.R., 2001. Influência do processo de determinação da cobertura de nuvens e dos aerossóis de queimada no modelo físico de radiação BRASIL-SR, Tese de doutoramento, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, 330 pp.

Martins, F.R., 2003. Cross validation of SWERA's core radiative transfer models – First and Second Reports. SWERA Latin America. Available at SWERA website: <http://www.cptec.inpe.br/swera/EN/bdd/bdd_pub.html>.

Martins, F.R., Pereira, E.B., 2006. Parameterization of aerosols from biomass burning in the BRASIL-SR radiative transfer model. Solar Energy 80, 231–239.

Martins, F.R., Souza, M.P., Pereira, E.B., 2003. Comparative study of satellite and ground techniques for cloud cover determination. Adv. Space Res. 32 (11), 2275–2280.

Martins, F.R., Pereira, E.B., Yamashita, C., Pereira, S.V., Mantelli Neto, S., 2005. Base de dados climático-ambientais aplicados ao setor energético – Projeto SONDA. In: Proc. of XII Simpósio Brasileiro de Sensoriamento Remoto, INPE, São José dos Campos, Brazil.

Maxwell, E.L., George, R.L., Wilcox, S.M., 1998. A Climatological Solar Radiation Model. In: Proc. of 1998 Annual Conference, American Solar Energy Society, Albuquerque, New Mexico, pp. 505–510.

Pereira, E.B., Martins, F.R., Abreu, S.L., Couto, P., Stuhlmann, R., Colle, S., 2000. Effects of burning of biomass on satellite estimations of solar irradiation in Brazil. Solar Energy 68 (1), 91–107.

Sims, R.E.H., 2004. Renewable Energy: A response to climate change. Solar Energy 76, 9–17.

Stuhlmann, R., Rieland, M., Raschke, E., 1990. An improvement of the IGMK model to derive total and diffuse solar radiation at the surface from satellite data. J. Appl. Meteorol. 29 (7), 586–603.