HORIZONTAL VISIBILITY INFLUENCE ON THE BRAZILIAN SOLAR ENERGY ASSESSMENT: SURFACE AND MODEL DATA INTERCOMPARSIONS

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1. Introduction

Several studies indicates that the usage of renewable energy, especially solar, bring economic and social benefits. These benefits are associated with development of remote areas, which are not assisted by Brazilian interconnect energy system from conventional sources; with consequences to stability and planning of Brazilian energy programs to the reduction of direct dependence of fossil fuels and to the direct emission of greenhouse gases in the atmosphere. However, a significant barrier to solar resource expansion as source of energy, to both electricity generation and water heating, is to provide reliable information required to understand available resources and its variability.

To the assessment of the solar energy resource, Renewable Energy Group from CPTEC/INPE and CCST/INPE uses the radiative transfer model BRASIL-SR to verify the availability and development of sceneries to this renewable source. The model uses geostationary satellites images and climatological data as input data to parameterize solar radiation interaction processes in atmosphere.

The SWERA project (Solar and Wind Energy Resource Assessment), financed by GEF/UNEP, was aimed to provide a consistent and secure environmental database with high reliability and accessibility. The main objective was to motivate the insertion of renewable energies on the electricity matrix of development countries, like Brazil (Pereira *et al.*, 2007). The BRASIL-SR model was used to provide the solar irradiation estimates from 1995 to 2005, what resulted in the publication of Brazilian Solar Energy Atlas (Pereira *et al.*, 2007). The results were quite coherent, being validated by project SONDA stations data and automatic meteorological stations operated in Brazil by CPTEC/INPE. However, when BRASIL-SR parameterize atmospheric aerosols just basing in climatological values of horizontal visibility, the model does not consider important conditions for quantify the amount of atmospheric aerosols in the atmosphere such as biomass burning and pollution sources from megacities and industrial areas. These factors can increase significantly the concentration of particles and greenhouse gases (Raes *et al.*, 2000), specially during dry season.

Seasonal variability of meteorological conditions has a direct influence on suspension aerosol amount in the atmosphere. With the beginning of dry station in Brazil Mid-West region, favorable conditions to biomass burning are observed, which can be caused by natural ways or anthropic actions. Besides, the aerosol atmospheric residence time is bigger during the dry season due to the smallest retreat of these aerosols by mixing processes and precipitation (Andrade *et al.*, 2004; Freitas, 2003).

Aires and Kirchoff (2001) affirm that the special distribution of biomass burning in Brazil is not uniform, and there is a contrast between source and non-source areas of biomass burning aerosols; related to climatic or regional factors. However, even in areas with less biomass burning, high concentrations of trace gases generated by biomass burning can be found, due to atmospheric transport.

The complex influence of aerosols in radiative balance has been evaluated in several studies. It considered up to 80% of biomass burning occurs in the tropics, producing a large amount of gases and particles (Crutzen and Andreae, 1990), affecting the radiative balance (Kaufman and Tanré, 1998; Christopher *et al.*, 2000) and consequently the thermal balance of the atmosphere. Other studies also show indirect effects, through the reduction of the evaporation and precipitation, besides the climatic effects (Ward *et al.*, 1992; Botkin and

Keller, 1995; Nobre *et al.*, 1998). According to IPCC (2007), atmospheric aerosols has a global radiative forcing up to -0.50 ± 0.40 W/m^2, while the global indirect effect is about -0,70 W/m^2 (ranging from -1.8 to -0.3 W/m^2). Comparing to the radioactive forcing of CO2 of +1.55 W/m^2, from +1.49 to +1.83 W/m^2, their contribution is quite significant.

Anderson *et al.* (1996) verify attenuation in the radiative forcing up to 25 W/m^2 in the surface, due to the increase of the optical thickness with the biomass burning. Procópio *et al.* (2003; 2004) also affirm that high concentration of aerosol particles generate a significant radiation deficit in surface, with instantaneous picks reaching up to -300 W/m^2 and average values in Alta Floresta during biomass burning season of -28 W/m^2. Castanho (1999) find indications of breeze contamination that arrives in the city of São Paulo from industrial area of Great ABC by resuspension of soil dust and photochemical formation of O_3 for the emitted precursors, besides the significant influence of the particulate matter emitted by vehicles.

2. Data and Methodology

2.1. BRASIL-SR radiative transfer model

BRASIL-SR is a physical model used to obtaining incident solar radiation estimates in the surface. It has been developed by the Group of Study of Renewable Energies of National Institute of Space Research (CCST/INPE) with the Federal University of Santa Catarina (UFSC), based in the German model IMGK (Stuhlmann *et al.*, 1990). It is based on the "Two-Flow" approach to solve the equation of radiative transfer and uses air temperature, surface albedo, relative humidity, horizontal visibility climatological data and elevation of the surface as input data. The model also needs information of cloud covering obtained from satellite images. The model assumes that cloud covering is the main factor of modulation of the atmospheric transmittance (Martins, 2001).

The effective cloud covering coefficient, C_{eff}, is determined by a linear relationship of clear sky and cloud conditions. This coefficient states the contribution of the cloud optical thickness to solar attenuation in the terrestrial atmosphere:

$$C_{eff} = \frac{L_r - L_{clr}}{L_{cld} - L_{clr}} \quad \text{(eq. 1)}$$

where L is the visible radiance measured by GOES channel 1 (0.52–0.75 µm), L_{clr} and L_{cld} are the measured radiances in the same channel in clear sky and cloud conditions, respectively, produced by image statistical analyses.

The identification process of clear sky and cloudy sky situations uses an algorithm that evaluates the relationship of infrared (4-10.2-11.2 µm) and visible channels (1-0.52-0.75 µm) radiances measures for each pixel (Martins *et al.*, 2003). Martins and Pereira (2006) mention the reliability of C_{eff} is an important factor of the solar estimates accuracy.

After the treatment of climatological and satellite data, the model solves the radiative transfer equation using the "Two-Flux" approach. Solar radiation spectrum is divided in 135 intervals and the atmosphere in 30 layers. The radiative processes is considered as an interaction with clouds, Rayleigh scattering (due atmospheric gases), absorption of atmospheric gases (O_3, CO_2 and water vapor), and Mie scattering (due aerosols). Each constituent concentration, as well temperature and the thickness of each atmospheric layer, are established based in the atmosphere type, selected by climatological value of surface air temperature. In BRASIL-SR model, the solar radiation flux in the top of the atmosphere F0 is lineally distributed among the two extreme atmospheric conditions, clear sky and cloudy sky. It also assumes the presence of linear relationship between the global irradiance in the surface and the radiation flux reflected from the top of the atmosphere, in the way of solar irradiation in the surface $F_{\downarrow}$ is obtained by equation 2, after obtaining the transmittances:

$$F_{\downarrow} = F_0\{\tau_{clear}(1 - n_{eff}) + \tau_{cloud} n_{eff}\} \quad \text{(eq. 2)}$$

Colle e Pereira (1998) demonstrated, in study developed for the Brazilian territory, that the use of this approach, quite simple, presents good results. The fluxgram in Figure 1 shows the execution sequence of the model.

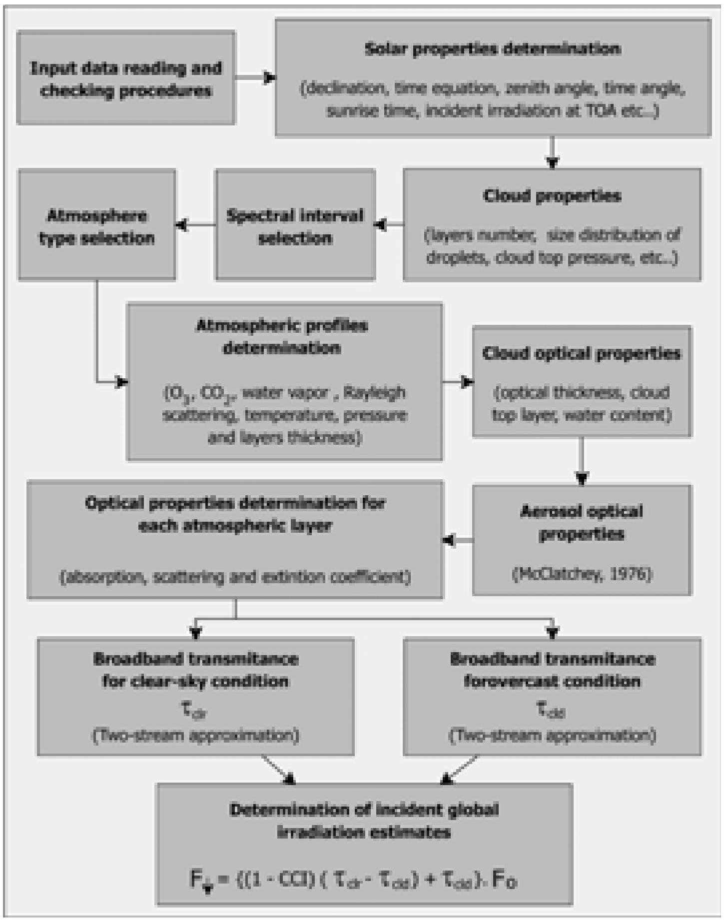


Fig. 1: BRASIL-SR model fluxgram. Source: Martins *et al.*, 2001.

The reliability evaluation of solar radiation estimates supplied by BRAZIL-SR was accomplished in two stages: firstly an intercomparison of radiative transfer models adopted by SWERA project to solar potential assessment in participant countries, with HELIOSAT (Rigollier *et al.*, 2004), SUNNY/ALBANY (Zelenka and Perez, 1986; Perez *et al.*, 1987a; Perez *et al.*, 1987b) and DLR (Diekmann *et al.*, 1988). The results of this phase showed that BRASIL-SR was presented similar results of other models, without anyone present statistically significant advantage by the others (Beyer *et al.*, 2004).

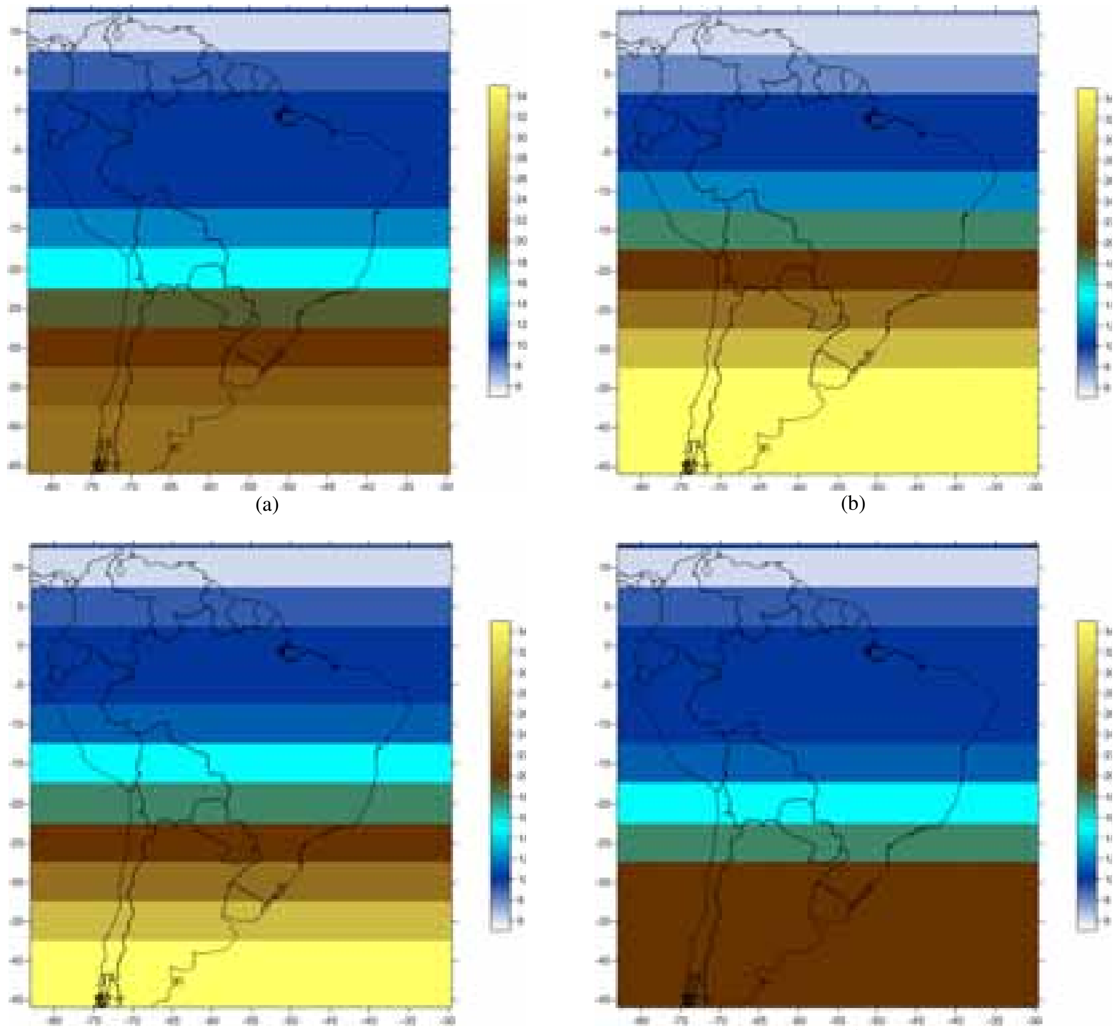
In the following stage, the estimates supplied by BRASIL-SR model were compared with measured values in surface stations belonging to SONDA and meteorological automatic stations operated by CPTEC. It was verified that the model overestimates the radiation flow over all Brazilian territory, with larger values to lower solar radiation flux (Pereira *et al.*, 2007).

Studies showed that estimates of solar irradiation at the surface supplied by BRASIL-SR model present an average deviation of 6% and a medium quadratic deviate in order of 12%, when compared with data collected in surface stations away from the locals of biomass burning (Pereira *et al.*, 2006). Other works (Christopher *et al.*,1996; Eck *et al.* ,1998; Gambi *et al.*, 1998, Procópio *et al.*, 2003; Procópio *et al.*, 2004) found relationships between higher concentration of atmospheric aerosols and increase of the deviation in the estimates models.

2.1.1. BRASIL-SR aerosol parametrization

In BRASIL-SR model, aerosol concentration in atmospheric layers is determined by the climatological continental profiles developed by McClatchey *et al.* (1972), modified in the lower 5 km following the climatological values of horizontal visibility at sea surface level (Leckner, 1978; Selby and McClatchey, 1975).

Climatological horizontal visibility is set to vary monthly and spatially to latitudinal strips of 5 degree. These values were obtained from data measured on surface stations with non-homogeneous distribution and with reduced number in Southern Hemisphere (Stuhlmann, 2000). The empiric correction of the atmospheric profile follows an exponential formulation as function of elevation. However, the climatological horizontal visibility database overestimates the visibility condition observed in areas of biomass burning and pollutant emissions in megacities. The Figure 2 presents the climatological horizontal visibility used by BRASIL-SR model, to March, June, September and December.



(a) (b)

(c) (d)

Fig. 2: Climatological horizontal visibility (km) used by BRASIL-SR model, to March (a), June (b), September (c) and December (d).

The transmittance to aerosol direct solar radiation is based in Angström (1964) formulation:

$$\tau_{a\lambda} = e^{\left(-\beta\lambda^{-\alpha}m\right)} \quad \text{(eq. 3)}$$

where β is Angström turbidity coefficient, α is the wavelength exponent, λ is the wavelength of solar radiation and m is the optical mass of the aerosols. This product is modeled in three altitude intervals: lower than 2 km, between 2 and 10 km and higher than 10 km.

It is important to mention that previous studies indicated that the use of climatological values of horizontal visibility resulted in satisfactory radiation estimates for clear sky conditions, in the case of low aerosol emission from anthropic sources (Pereira *et al.*, 2007). Martins and Pereira (2006) affirm that estimates accomplished by BRASIL-SR model in megacities areas, or in biomass burning occurrence areas, that has conditions out of the climatological horizontal visibility averages present high deviations, could reach values of up to 60% in some days of the year.

2.2. Horizontal visibility database generation

Due to the incoherence found in the spatial variability of the climatological horizontal visibility database used by BRASIL-SR model, it was chosen to use a new database that could be monthly updated in order to represent more satisfactory both seasonal and spatial variability. This is an important factor that conditions and areas with a high load of aerosols were well represented, what would bring more fidelity to the atmospheric conditions parameterized by BRASIL-SR and directly related with results accuracy. At the same time, it was concerned that meteorological events and extreme conditions had not contaminate this new database of horizontal visibility somehow.

Bearing this in mind, daily averages of horizontal visibility and daily lowest, highest and average of relative humidity from 77 airports of the whole South America were analyzed from 2007. Hourly date of horizontal visibility, air temperature and dew point temperature from Meteorological database of CPTEC/INPE, added other 28 airports in the Brazilian territory for the same year, combining a total number of 105 stations. The spatial distribution of these stations is presented in Figure 3.

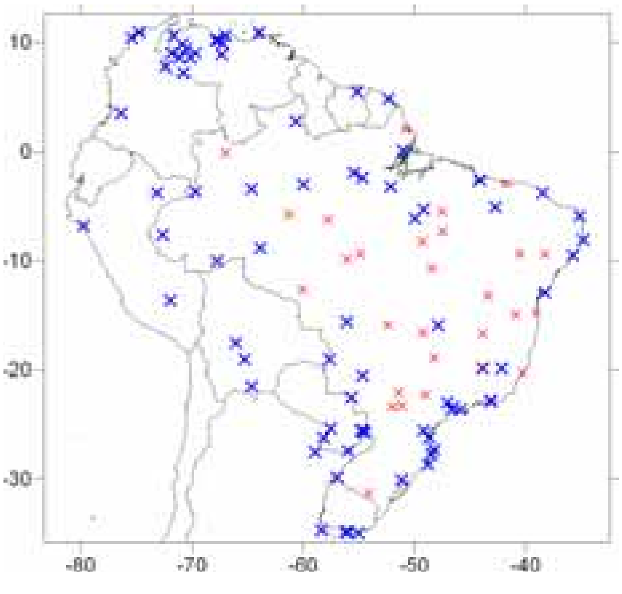


Fig. 3: Spatial distribution of data used to generation of database of horizontal visibility. In blue, daily stations data; in red, hourly station data.

The data collected at these stations were pre-processed, where the exclusion of registers of very low horizontal visibility values due to the presence of hidrometeors, normally caused by meteorological phenomena as fog or strong rain, relating them with datapoints of relative humidity higher then 90%. In case of hourly data, a similar criterion was applied, but the registers were excluded where the difference between air temperature and dew point temperature stayed lower than 2.2 ºC.

To eliminate horizontal visibility outliers in the hourly dataset, present time information was used to select and to confront to manually verification and exclusion ion case of incoherent data.

This method was suggested by Husar *et al.* (2000) and it minimizes the possibility to insert in the horizontal visibility database any condition of extreme events not associated with biomass burning or aerosol load by the megacities. A third routine transformed data in monthly averages, and interpolations could be accomplished. Kriging interpolation was used as the stations were irregularly spaced.

2.3. Solar irradiation data

Solar irradiation data by solarimetric stations from SONDA were used to validate BRASIL-SR model. The objective of this sampling net was build a reliable meteorological database to help the development and improvement of numerical models to assess solar and wind energy resources in Brazil. The data measured by SONDA have quality control based on reliable WMO (World Meteorological Organization) criteria (Wounds *et al.*, 2006; BSRN, 2011; WEBMET, 2011). These stations are distributed over Brazilian territory, in way to represent all the regions (Figure 4).

Fig. 4: SONDA stations localizations, in brazilian territory.

3. Results

3.1. Horizontal visibility database to year 2007

After primary processing and treatment of all horizontal visibility data from year 2007, was verified higher visibility values in March, for all Brazilian regions, while lower values were observed in September, also for all regions. Values were reducing gradually from March to September; and increasing back again to maximum values in March.

Figure 5 shows the horizontal visibility variability in 2007 and the seasonal variability of the horizontal visibility was observed. March has some nuclei with smaller amounts - about 9.7 km in the North, and the highest values were observed in the South and Northeast. In June, the continent was virtually split in half, with higher values verified in the North, with extremes values around 10.6 km in the North-Northeast of Brazil; in the South, the lower values were around 8.7 km. September is characterized by a huge core in the center-north of Brazil, with values reaching down to 6.7 km of horizontal visibility; by the way, the visibility observed in the Brazilian Northeast is around 10 km. In December, the horizontal visibility reaches values around 9.5 km across South America, with a small nucleus around 9.8 km in the Northeast Brazil.

3.2. BRASIL-SR model difference maps

Simulations with BRAZIL-SR model were accomplished, to March, June, September and December, 2007, using these two horizontal visibility databases: the climatological database, with resulted already established and validated in previous studies and the new database of horizontal visibility, developed in this work. From these two results, maps of difference were generated between simulations with the climatological visibility and simulations with the updated database, for comparison effects. They will be presented maps to March and September, because their fact to represent the extreme atmospheric conditions in terms of horizontal visibility, that is this work focus. Figure 6 presents the maps of difference for the year of 2007.

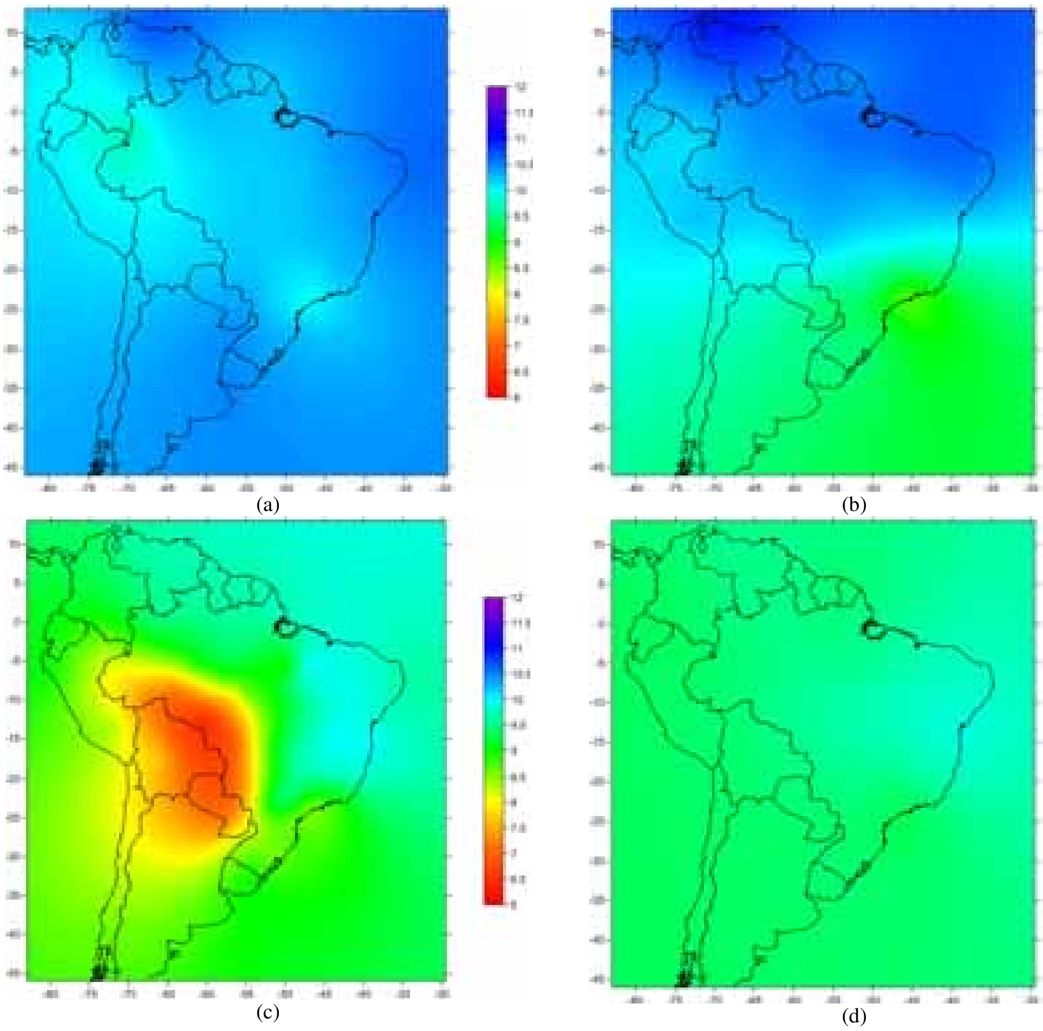
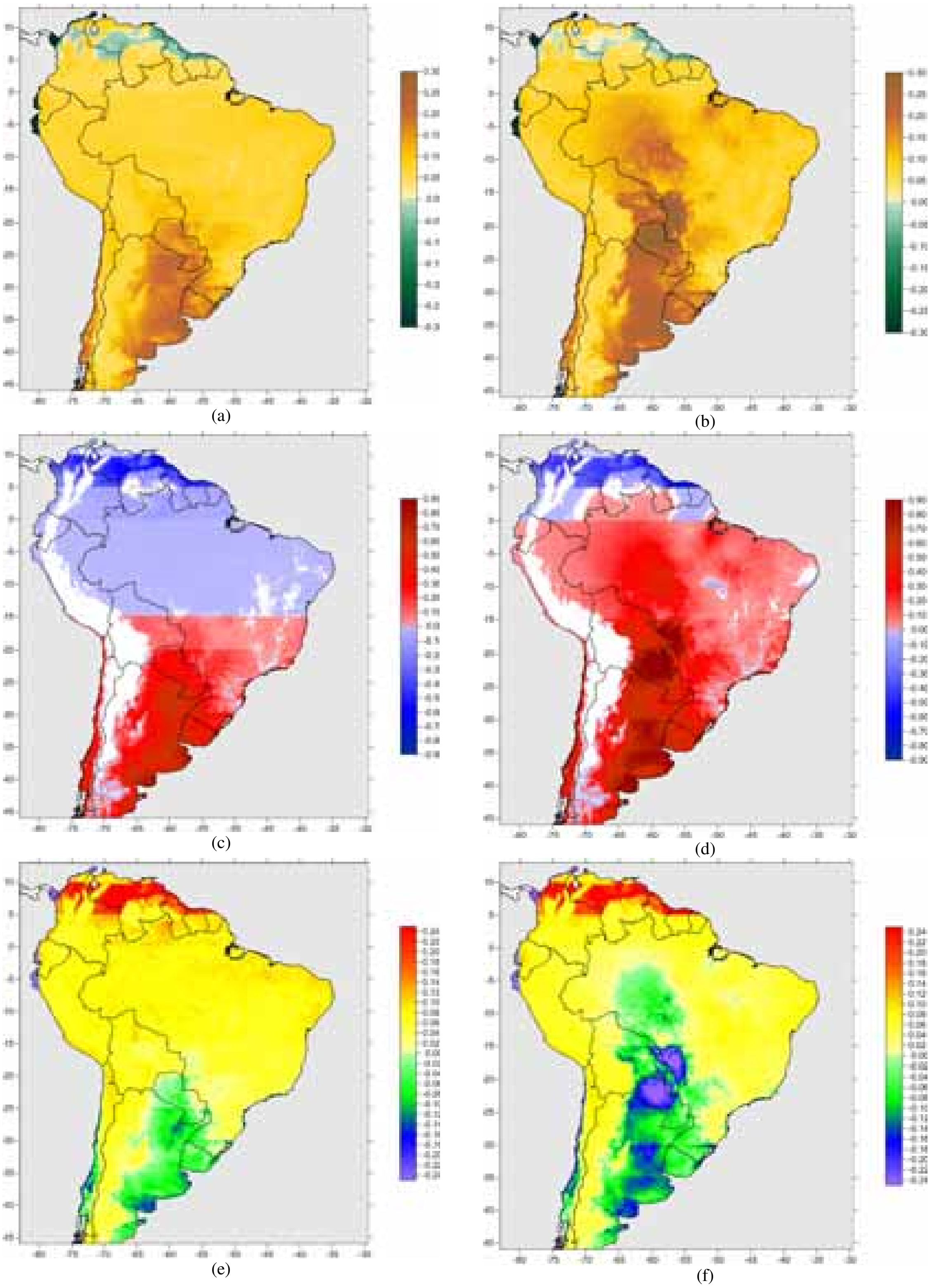

(a) (b) (c) (d)

Fig. 5: Horizontal visibility (km) to March (a), June (b), September (c) and December (d), 2007.

The year of 2007 has pronounced differences in maps, and this can be already observed in the global radiation maps (Figures 6-a and 6-b). Positive trends is observed, however in a more evident way in September, where the higher values are found in North, Mid-west and South of Brazil areas, with values up to 0.36 kWh/m^2. In March, is observed the higher values in Mid-West and South regions, around 0.13 kWh/m^2. Direct radiation (Figures 6-c and 6-d) follows same pattern, with more pronounced differences in September, where are observed difference values up to 1.1 kWh/m^2. Differences up to 0.49 kWh/m^2 were observed in South Brazil in March. The differences observed in the diffuse radiation (Figures 6-and and 6-f) are also more significant in September and observed in North, Mid-west and South of Brazil, with minimum values up to -0.32 kWh/m^2. March has minimum values up to -0.16 kWh/m^2 in the South Brazil.

3.3. Measured data and simulated data intercomparisons

To evaluate results from the BRASIL-SR model using the climatological horizontal visibility and the updated horizontal visibility databases, intercomparisons were accomplished with measured surface data by SONDA stations that were closer to the areas where the largest horizontal visibility differences occured.



(a) (b) (c) (d) (e) (f)

Figure 6 - Difference maps between simulations using climatological visibility database and simulations with updated visibility database, in kWh/m^2, for 2007. Differences are presented between global radiation modeled in March (a) and September (b); direct radiation modeled in March (c) and September (d) and diffuse radiation modeled in March (e) and September (f). Positive values (negative) indicate areas where the estimates with the updated horizontal visibility database were lower (higher) that those ones with climatological horizontal visibility database.

Three of these stations are located in the Mid-west Brazil, where larger biomass burning are verified. Table 1 shows the stations used in model integrations evaluation of BRASIL-SR model.

Tab. 1: SONDA Stations used in the evaluation of the results of BRASIL-SR model.

SITE	LATITUDE	LONGITUDE	ALTITUDE (m)
Brasília – DF, Brazil	15° 36' 03" S	47° 42' 47" W	1023
Campo Grande – MS, Brazil	20° 26' 18" S	54° 32' 18" W	677
Cuiabá – MT, Brazil	15° 33' 19" S	56° 04' 12" W	185
São Martinho da Serra – RS, Brazil	29° 26' 34" S	53° 49' 23" W	489

Table 2 shows comparison for the two experiments of the root mean square and bias for BRASIL-SR results in March and September for 2007 respectively.

Tab. 2: RMSE and BIAS (in%) of BRASIL-SR integrations results, using the climatological visibility and the updated visibility, to March and September, 2007.

Brasília (-47.72 -15.60)	**Global (%)**		**Direct (%)**		**Difuse (%)**	
	Mar	**Sep**	**Mar**	**Sep**	**Mar**	**Sep**
RMSE Climatologic Model	23.32	17.57	34.19	20.81	26.79	21.50
RMSE Updated Model	24.40	18.60	34.30	21.06	27.59	20.09
BIAS Climatologic Model	16.58	11.43	20.29	15.21	5.23	-10.87
BIAS Updated Model	17.88	12.77	20.43	15.55	8.68	-7.79

Cuiabá (-56.06 -15.55)	**Global (%)**		**Direct (%)**		**Difuse (%)**	
	Mar	**Sep**	**Mar**	**Sep**	**Mar**	**Sep**
RMSE Climatologic Model	7.25	27.44	*	*	*	41.39
RMSE Updated Model	9.36	21.71	*	*	*	23.45
BIAS Climatologic Model	7.23	-26.20	*	*	*	41.39
BIAS Updated Model	9.34	-20.44	*	*	*	19.89

Campo Grande (-54.53 -20.40)	**Global (%)**		**Direct (%)**		**Difuse (%)**	
	Mar	**Sep**	**Mar**	**Sep**	**Mar**	**Sep**
RMSE Climatologic Model	15.59	10.34	*	*	22.64	37.78
RMSE Updated Model	16.24	6.37	*	*	23.60	32.36
BIAS Climatologic Model	11.47	-5.32	*	*	0.51	27.65
BIAS Updated Model	11.64	-2.74	*	*	1.67	18.42

São Martinho da Serra (-53.81 -29.45)	**Global (%)**		**Direct (%)**		**Difuse (%)**	
	Mar	**Sep**	**Mar**	**Sep**	**Mar**	**Sep**
RMSE Climatologic Model	12.66	17.62	33.64	51.48	28.80	43.71
RMSE Updated Model	12.51	15.45	26.83	44.87	28.91	40.27
BIAS Climatologic Model	1.89	-12.98	-19.69	-37.32	18.56	13.49
BIAS Updated Model	2.39	-8.84	-12.58	-31.23	19.13	9.59

4. Discussion and conclusions

The horizontal visibility data from airports has a subjectivity condition, but has a great importance in inference of atmospheric particles amount; after all, it is supposed that when low values of horizontal visibility are observed (except in adverse meteorological conditions), a dry-fog or smoke condition is associated, and this can be biomass burning or pollution result. The main objective of this horizontal visibility database update is bringing to the model this type of information, especially in the spacial and seasonal variability of the atmospheric aerosols. In the case of horizontal visibility database proposed by McClatchey *et al.* (1972) and presented in the Figure 2, it is especially important to eliminate the latitudinal way as the climatological data are willing, distributing in a more discerning way and respecting the Brazilian regions characteristics.

Analyzing data of 105 stations in the whole South America (Figure 4) for a year period, it was looked to bring this reality to the model. However, is important to understand that punctual events, as biomass burning which happens in a specific place, a specific day in the month, are treated in a softened way when monthly averages of horizontal visibility are generated. Nevertheless, the horizontal visibility database shown in this paper in Figure 5, is quite coherent with total monthly biomass burning occurrences, and was expected this represent an average condition of aerosols amount in the atmosphere. In Brazil, the Division of Environmental Satellites (DSA) of CPTEC/INPE accomplishes the identification of biomass burn occurrences.

The year of 2007 had a larger amount of biomass burn focuses detected (202299 focuses). It was identified 2346 focuses in March; 4906 in June; 63200 in September and 5557 in December. The great amount of biomass burning occurrences in September is represented in the Figure 5-c, with the smallest values of horizontal visibility in the Center-north of the Brazilian territory. The updated horizontal visibility database has shown coherent with biomass burning occurrences were observed in this same period. Important to mention that in the three analyzed years, the stations Southeast Brazil presents a tendency of visibility decrease, in spite of low visibility values softened by the interpolation process and by monthly averages. That can have some relationship with industrial activities and gases and particules emission.

From BRASIL-SR model integrations results of March and September, 2007, maps of difference of Global, Direct and Difuse radiation were generated. Those maps always shows the values obtained in the simulations using the climatological base of visibility minus those ones obtained in the simulations using the base of updated visibility. In all maps, latitudinal lines are showed, and it is a reflex of the climatological values of horizontal visibility. Horizontal visibility values are the same ones inside these 5° latitude strips, the maps of difference presents this same pattern. In general, great differences are observed where the values of horizontal visibility are more contrasting. That happens in areas where large aerosol amounts were observed and in the Center-South Brazil regions, where large differences of climatological values were observed.

This analyses, from a year with a large aerosol intraseasonal variability, present more defined nuclei in the difference maps of September (Figures 9-b, 9-d and 9-f), that are compatible with the biomass burning detected in this period. The comparisons with measured data in Campo Grande, Cuiabá (in Mid-West Brazil) and São Martinho da Serra (in the South Brazil) stations presented improvements in RMSE and BIAS values (table 3). However, the adjustments increased, although in a discreet way, RMSE and of BIAS of the global, direct and difuse radiation on March.

The updated horizontal visibility database brought more interesting results for the areas where biomass burning happens and where has large discrepancy of climatological values, but they were not effective where the horizontal visibility is naturally higher, for all of the simulated months. An explanation for that comes from an important modulation factor of atmospheric transmitance of BRASIL-SR model, that is the identification of clear and covered sky conditions. When assuming the solar radiation flux in the top of the atmosphere is lineally and distributed among these two extreme atmospheric conditions, the determination of the incident solar irradiation in the surface is reduced to the calculation of the atmospheric transmitance in these outline conditions. In the model, the clear sky component is parametrized in function of surface albedo, solar zenital angle and atmospheric representatives optic thickness (including the aerosols); to covered sky component, it is function of the solar zenital angle and the optic thickness / altitude of the top of the clouds.

In other words, clouds induces no systematic mistakes, result of the simplified parametrizations and like this, reducing the correlation between estimates and measured values. That happens because cloudiness and atmospheric aerosols are first and second order parameters in the irradiation estimates in the surface. When assuming that the cloudiness is the main modulation factor of the solar radiation, it discards the importance of the aerosols in the remaining process, what can explain to the variability of the results of RMSE and BIAS presented in the Table 2. These error variability would be directly associated with the cloudiness and the precipitation of 2007.

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