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Parameterization of aerosols from burning biomass in the Brazil-SR radiative transfer model

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Abstract

A new aerosol parameterization was developed and implemented for operational use with the BRASIL-SR model. The goal is to improve the assessment of solar energy resources in Brazil. Optical properties of the aerosols from burning biomass were obtained using software package OPAC and are in good agreement with previous field measurements made in Brazil. Three different mixture ratios of black carbon were used to cover the full range of typical measured values. The atmospheric transport model SMOKE provided the aerosol profile. An evaluating period of 11 days in August/1995 and ground measurements from six sites situated in Amazon region was used to validate the results. The global solar irradiation estimates obtained with new aerosol parameterization, presented smaller mean bias error in all ground sites. The correlation among estimates and measured values for surface global solar irradiation improved about 2.5 times by adopting an aerosol composition with 5% of black carbon.

Keywords: Solar radiation; Radiative transfer model; Biomass burning aerosols

1. Introduction

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 a growth of the energy demand of 4% in those countries, i.e. a duplication in the next 17 years (Goldemberg, 1998). Solar energy is a renewable source of energy with minor environmental impact and it is becoming technically and economically feasible (Pereira and Colle, 1997). Reliable assessment of solar energy is essential for in-country energy policy and planning mostly in developing countries.

Information on the optical properties and the geographical distribution of atmospheric aerosols has great influence on the reliability of the solar irradiation estimates (Box et al., 1996). Uncertainties in surface solar irradiation estimated by computational methods result from geographic variability of aerosols in the atmosphere by natural phenomena and induced forest fires

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Nomenclature

ABRACOS	Anglo-Brazilian Amazon Climate Observation Study
BC	black carbon
BSRN	baseline solar radiation network
CPTEC	Centre for Weather Forecast and Climate Studies
$F_\downarrow$	surface solar irradiation
F_0	extraterrestrial solar irradiation
INPE	Brazilian Institute for Space Research
IR	infrared radiation
LABSOLAR	Solar Energy Laboratory
n_{eff}	effective cloud cover coefficient
OPAC	Optical Parameters of Aerosols and Clouds
rRMSE	relative root mean square error, i.e. ratio among root mean square error and mean value of ground data
rMBE	relative mean bias error, i.e. ratio among mean bias error and mean value of ground data
SCAR-B	Smoke/Sulfates, Clouds and Radiation—Brazil Experiment
UFSC	University of Santa Catarina
TRACE-A	Transport and Chemistry near the Equator Experiment over the Atlantic
UTC	Universal Time
VIS	visible radiation
WMO	World Meteorological Organization
τ_{clr}	clear sky transmittance
τ_{cld}	overcast sky transmittance

in addition to uncertainties on the cloud cover variability (Pinker and Laszlo, 1989). Aerosols from biomass burning events play an important role in radiative processes in the atmosphere and can attenuate the global solar radiation incident at surface. Studies have shown that a radiative forcing of about $-25\ W/m^2$ at surface can be expected by the increase of the optical depth caused by the aerosols from burning biomass (Anderson et al., 1996). Whitlock and Tarpley (1996) have shown an overestimation in the surface solar irradiation of up to $120\ W/m^2$ by the presence of forest fire combustion products in atmosphere (including aerosols) near measurement sites in Africa.

Systematic deviations between ground measurements and model estimates of solar irradiance in clear sky conditions were up to 2.5 times larger near induced forest fires in Brazil (Pereira et al., 2000). The mean bias error for sites close to regions of intensive induced fires during clear sky condition grows up to the same order of that produced by clouds far from biomass burning areas (Martins, 2001; Pereira et al., 2000). Another important point must be kept in mind: in Brazil the areas with larger solar irradiation are located in a region where the number of fire spots peaks in dry season, as seen by the AVHRR satellite sensors (Colle and Pereira, 1998; Setzer et al., 1994).

This paper describes an improvement of the earlier work published by Pereira et al. (2000) where the influence of aerosols from biomass burning in Brazil on the surface solar irradiation is discussed. The main goal of this work is to describe a simple operational parameterization for the aerosol from burning biomass applied to the radiative transfer model, BRASIL-SR, and to show its results for the central region of Brazil, where most of induced fires occur during dry season.

2. Radiative transfer model BRASIL-SR

The Brazilian Institute of Space Research (INPE) and Solar Energy Laboratory at University of Santa Catarina (LABSOLAR/UFSC) are working together to develop a radiative transfer model, BRASIL-SR, to map the surface solar irradiation in Brazil. The BRAZIL-SR model is a physical model that combines satellite and climatological data with a "Two-Stream" radiative transfer scheme to solve the radiative transfer equation for atmosphere (Martins, 2001). A short description of the BRASIL-SR model will be presented here, since a more detailed description of BRASIL-SR model was presented before in this journal (Pereira et al., 2000).

The Fig. 1(A) 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 extraterrestrial solar irradiation. The first term is associated with clear sky condition, and the second one is related with overcast condition. The clear (τ_{clr}) and cloudy (τ_{cld}) transmittances can be obtained from atmospheric parameterization using climatological data (temperature, relative humidity, surface albedo, visibility and cloud properties) and geographical position (latitude, longitude and altitude). The effective cloud cover coefficient, n_{eff}, 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).

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

The confidence and reliability of the n_{eff} is a chief factor to get solar estimates with good accuracy. The n_{eff} value contains information about spatial distribution and

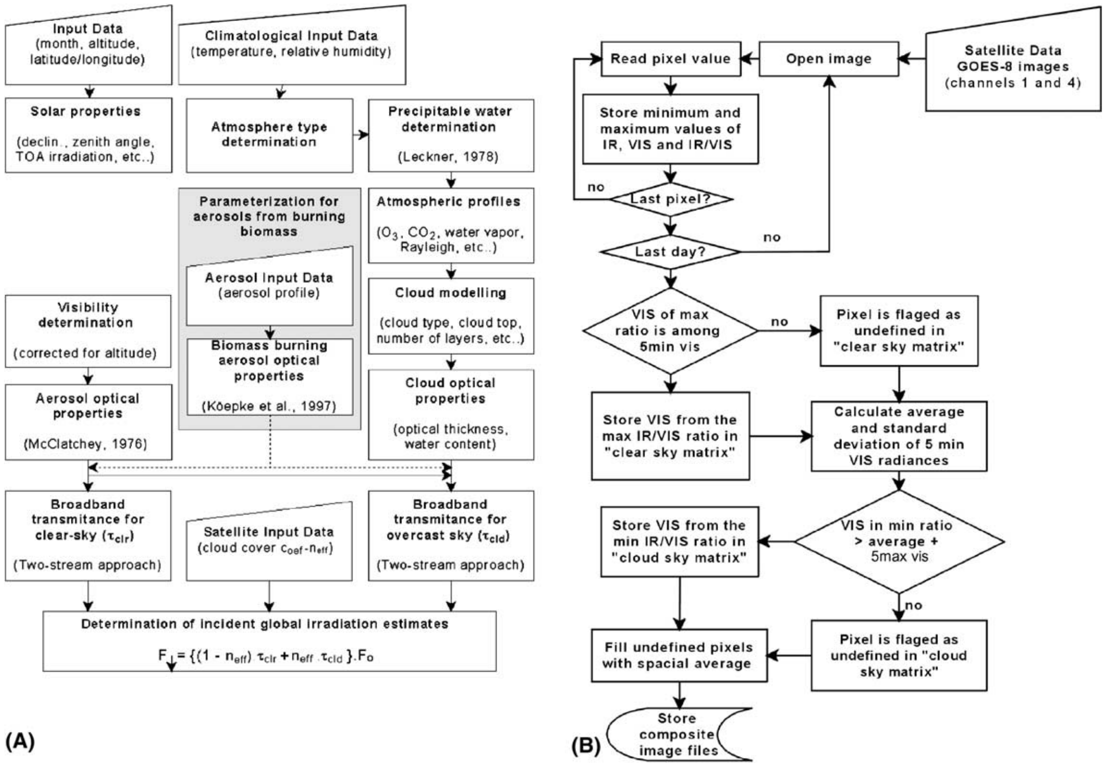

Fig. 1. (A) Schematic diagram of BRASIL-SR radiative transfer model. The gray box procedures were implemented to provide optical properties for aerosols injected to the atmosphere by induced fires. These optical properties were used, together with optical properties for other atmospheric constituents, in ‘‘Two-Stream’’ algorithm in order to solve radiative transfer equation. (B) Schematic diagram of algorithm to obtain clear and overcast composite images used in cloud cover index determination.

optical thickness of clouds and it is obtained as described in Eq. (2), where L is the visible radiance measured by channel 1 (0.52–0.75 μm) of GOES-8 satellite, and L_{clr} and L_{cld} are, respectively, the visible radiances measured by the same channel in clear sky and overcast conditions.

$$n_{eff} = \frac{[L - L_{clr}]}{[L_{cld} - L_{clr}]} \quad (2)$$

The composite images with L_{clr} and L_{cld} values are produced by statistical analysis of GOES-8 satellite images. Fig. 1(B) presents a flowchart for algorithm, called ‘‘Ratio IR/VIS’’, used to produce both composite images. This algorithm uses the ratio among infrared (channel 4–10.2–11.2 μm) and visible (channel 1–0.52–0.75 μm) radiances measured by GOES-8 satellite for each image pixel to help in identifying clear and overcast sky days (Martins et al., 2003). The use of bi-spectral analysis of satellite data allows for a better identification of clouds as described in Desbois et al. (1982).

The largest ratio values are associated with surface characteristics (in the absence of snow cover): high temperature and reduced albedo. With this in mind, the clear sky composite image will be filled with visible radiances that produce the largest ratio IR/VIS and are among the five lowest visible radiances measured within a 1-month period. Otherwise, the pixel will be flagged as undefined condition.

In a similar way, the overcast composite images are filled with visible radiances that produces lowest ratio IR/VIS and are among the five largest visible radiances of the month in study. The undefined pixels in both composite images are filled with the spatial average of neighboring pixels.

The Fig. 2 presents a comparison between measured and estimated values of daily surface solar irradiation in clear sky days when no correction were applied to take in account the influence of the aerosols from burning biomass. Table 1 presents information for each measurement site used in the comparison. The acronyms rRMSE and rMBE are used to represent the ‘‘relative root mean square error’’ and ‘‘relative mean bias error’’, respectively. They are obtained by following equations using the modeled (estimated) values y, the measured values x and the amount of clear sky days N:

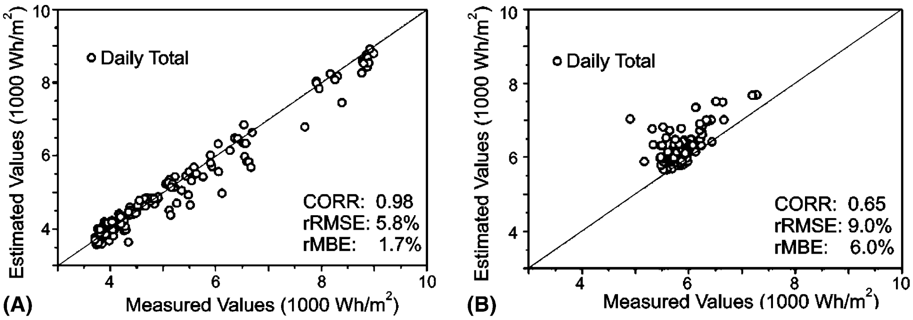

Fig. 2. Comparison between measured and estimated values of daily global solar irradiation for clear sky days. (A) At Santa Catarina (south region of Brazil) e (B) At Amazon region. (Colle and Pereira, 1998).

Table 1
Measurement sites used for validation of solar irradiation estimates provided by BRASIL-SR model

Id	Site	Latitude/longitude	Altitude (m)	rRMSE[a] (%)	rMBE[b] (%)	Clear sky days (#)	Instrumentation
1	Mina Potosi	9.78° S/62.87° W	80	nc[c]	43.6	1	Kipp and Zonen CM-5
2	Jarú	10.08° S/61.92° W	120	8.5	5.8	53	Kipp and Zonen CM-5
3	Aparecida	10.75° S/62.87° W	220	8.4	7.4	28	Kipp and Zonen CM-5
4	Ducke	2.57° S/59.95° W	80	nc[c]	9.3	1	Kipp and Zonen CM-5
5	Boa Sorte	5.17° S/48.75° W	170	6.6	6.4	8	Kipp and Zonen CM-5
6	Rio Doce	5.75° S/49.17° W	150	7.2	6.4	14	Kipp and Zonen CM-5
7	Cuiabá	15.33° S/56.07° W	152	nc[c]	17.1	1	Kipp and Zonen CM-5
8	Florianópolis	27.60° S/48.57° W	15	4.9	1.2	121	Kipp and Zonen CM-11
9	Lebon Régis	26.98° S/50.71° W	1036	2.8	−0.4	8	Kipp and Zonen CM-11

The clear sky days were observed in 1995 to 1996, except for Florianópolis with data from 1994 to 1997. Sites 1–7 are located in Brazilian Amazon region and sites 8 and 9 are located in South region of Brazil.
[a] rRMSE—root mean square error relative to mean measured global solar irradiation.
[b] rMBE—mean bias error relative to mean measured global solar irradiation.
[c] nc—not enough data.

$$\mathrm{rMBE} = \frac{\sum_{i=1}^{N}(y_i - x_i)}{\sum_{i=1}^{N}x_i} \tag{3}$$

$$\mathrm{rRMSE} = \left(\frac{\sum_{i=1}^{N}(y_i - x_i)^2}{N}\right)^{1/2}\left(\frac{\sum_{i=1}^{N}x_i}{N}\right)^{-1} \tag{4}$$

Fig. 2(A) shows the good agreement between estimated values of daily surface solar irradiance provided by BRASIL-SR model and the ground truth values measured in two ground stations both located in Santa Catarina state (South Brazil), far from the zone of induced forest fires. The BSRN (WMO-Baseline Solar Radiation Network) site of Florianópolis is located in a coastal city with the same name. The radiation site located in the city of Lebon Régis is 1000 m above sea level and it is submitted to the same procedures for maintenance and data qualification, as established for the Florianópolis BSRN site. The bias deviations in surface global solar irradiation estimated by model BRASIL-SR are about 2% of the daily average in clear sky days (0.4 MJ/m^2) in both measurement sites.

From Fig. 2(B), it can be noted that model BRASIL-SR overestimates surface solar radiation for clear sky days in the Amazon region where intensive forest fire activities take place. Ground data in Amazon data were collected as part of ABRACOS project (Anglo-Brazilian Amazon Climate Observation Study) and were subjected to strict quality control procedures. Table 1 shows that the rMBE may grow up to 45% (about 10 MJ/m^2) for clear sky days for sites close to the Amazonian and Central region of Brazil were large fire spot counts occurs. Since cloudy days were not considered and the model have presented good performance for clear sky days outside the regions of higher incidence of induced forest fires, the aerosols introduced in troposphere by biomass burning events are the chief reason for the largest dispersion and inaccuracy of solar irradiation estimates in central and north sites. Most of the clear sky days occur in dry season when the number of fire spots peaks in Amazon region (Pereira et al., 2000). The model BRASIL-SR makes use of very simple approaches to parameterize the aerosol transmittance: the Angstrom method (Angström, 1964) and the continental profile of aerosols tuned by visibility data. These approaches are not enough to model the spatial variability of aerosol and fails in polluted regions such as in urban and industrial areas

(Gambi et al., 1998), and in areas with seasonal events like induced forest fires (Martins, 2001). Additional information and more detailed discussion concerning the solar estimates uncertainties and biomass burning aerosols can be found in Pereira et al. (2000) and Martins (2001).

3. Parameterization of aerosols from burning biomass

The solar radiation reaching Earth's surface is reduced and the energy balance in the atmosphere is modified due to a combination of scattering and absorption in aerosol layers. This modification is usually referred to as the aerosol radiative forcing, which is the difference between the net radiation reaching Earth's surface with and without the aerosol layer. Christopher et al. (1996), Anderson et al. (1996) and Eck et al. (1998) found a net cooling effect in the atmosphere by the aerosol layers over the Amazon and over the Cerrado regions in Brazil.

A new aerosol modeling was implemented in order to improve the reliability of solar radiation assessment in Brazil. The software package OPAC (Hess et al., 1998) was used to calculate the optical properties for three different chemical compositions of aerosols. The three different mixture ratios of water solubles-insolubles particles, and soot were select in OPAC to reproduce the mixture ratios measured for aerosols emitted by induced forest fires in previous field experiments in the Amazonian region: TRACE-A and SCAR-B. The major difference between these three compositions is the mixture ratio of black carbon chosen in a way to cover the range of values observed in field missions: 5%, 7.8% and 10% of total aerosol mass. The black carbon (BC) component is of major concern for its distinctive low single scattering albedo that makes aerosols from biomass burning events higher absorber than aerosols from natural sources (Artaxo et al., 1998; Eck et al., 1998; Ferek et al., 1998). BC accounts for about 4–8% of the total aerosol mass released in biomass burning events in Brazil (Pereira et al., 1996, Reid et al., 1998), and BC mixture ratio presents a large variability even in a single event. This variability depends on the vegetation type, burning phase, humidity, and other factors.

The optical properties for all three aerosol compositions show good agreement with data and measurements obtained in TRACE-A and SCAR-B (Artaxo et al., 1998; Echalar et al., 1998; Eck et al., 1998; Ferek et al., 1998; Kotchenruther and Hobbs, 1998; Reid et al., 1998; Pereira et al., 1996). The Fig. 3 shows the optical properties of aerosols from burning biomass with 5% of black carbon as a function of solar radiation wavelength and relative humidity. Similar plots were obtained for other two compositions.

The atmospheric profile of aerosol from burning biomass was supplied by an operational atmospheric transport model, SMOKE, running at INPE-CPTEC and developed by Trosnikov and Nobre (1998). This model estimates the aerosol concentration in each atmospheric layer by considering the main large-scale atmospheric processes such as sedimentation, vertical and horizontal advection. The source of aerosols is calculated from the number of fire spots obtained in routine procedure by CPTEC by using orbital satellites NOAA (Setzer et al., 1994; http://www.cptec.inpe.br/queimadas/). The

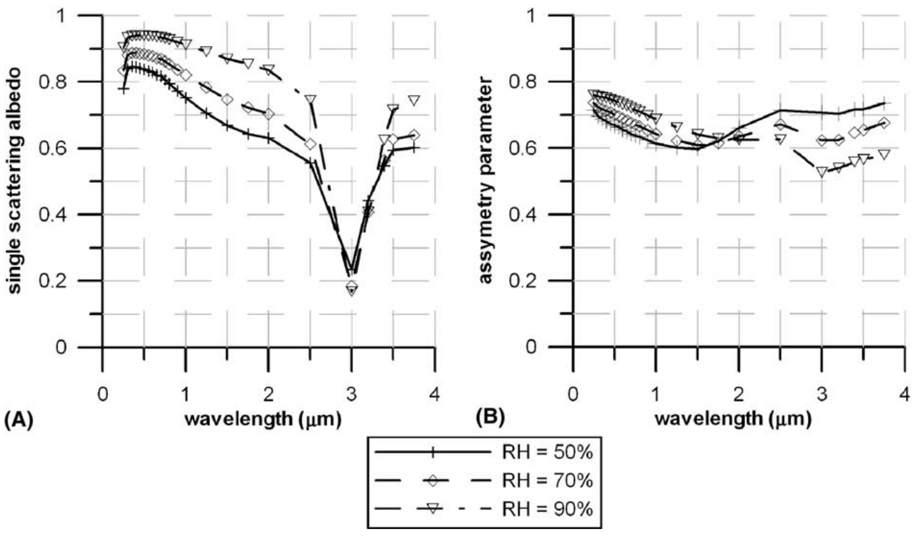

Fig. 3. Optical properties of aerosols from burning biomass with 5% of black carbon as a function of solar radiation wavelength: (A) single scattering albedo; (B) asymmetry coefficient. RH stands for relative humidity.

transport model runs jointly with the meso-scale model Eta and has access to wind, temperature and other climatic forecast information each 48-minute interval. The aerosol particle profile provided by the transport model has shown good agreement with data obtained from GOES-8 images and with geographical distribution observed during the SCAR-B experiment as demonstrated by Trosnikov and Nobre (1998).

The aerosol profile provided by the transport model, single scattering albedo and asymmetry coefficient provided by OPAC software were included into the "Two-Stream" algorithm used to solve the radiative transfer function in the BRASIL-SR model. The wavelength and relative humidity dependencies presented by both optical properties were taken into account in the new aerosol parameterization.

4. Validation procedure—results and discussions

The sites for radiation data acquisition 2–7 were used to evaluate the parameterization adopted for the aerosols from burning biomass. Eleven days (from 20 to 30/08/1995) were used in the validation procedure. This short period of time was used as a consequence of the high computational resources required by the atmospheric transport model that handles a great volume of data: forest-fire spots, wind velocity and direction, temperature, and others.

The daily global (diffuse + direct) solar irradiation was estimated by BRASIL-SR model in four different conditions. In three of them, the estimated values were obtained by using the parameterization of aerosols with three different mixture ratios of black carbon. In the fourth condition, the estimated values were obtained without applying the new parameterization.

Only clear sky days were used in the comparison between estimated and measured values in order to avoid intrinsic uncertainties associated with the cloud parameterization in the BRASIL-SR model. The criteria proposed by Iqbal (1983) was adopted to select clear sky days—$n_{\mathrm{eff}} < 0.2$. The Fig. 4 shows a better agreement among measured and estimated global solar irradiation when the proposed parameterization of aerosols is applied for Boa Sorte, Dimona and Ducke. These sites presented the lowest rMBE and rRMSE values and yielded the largest amount of clear sky days in the time period.

It is hard to evaluate the benefits of the parameterization for Aparecida and Rio Doce. Both sites presented only one day of clear sky during the validation period and it was the first day of the model run, when the devi-

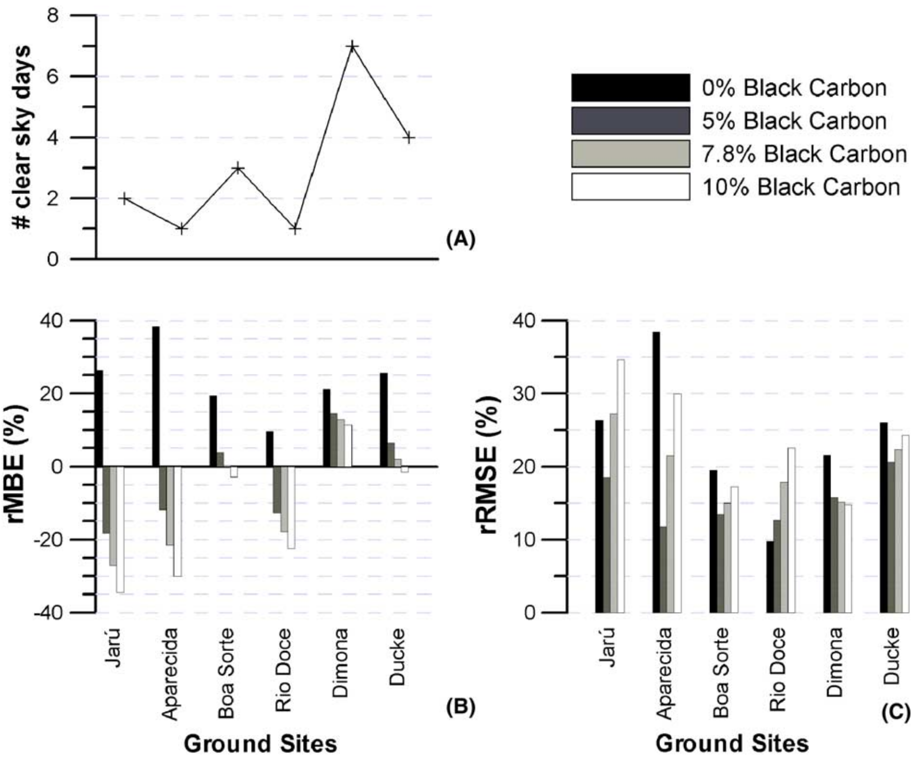

Fig. 4. Comparison between errors for daily global solar irradiation estimated by model BRASIL-SR with and without parameterization of aerosols from burning biomass: (A) number of clear sky days in each site in the time period from August 20 to August 31 (B) relative mean bias error (rMBE) values and (C) relative root mean square error (rRMSE) values.

ations of the transport model estimates were larger. The transport model assumes a simplifying hypothesis of no fire spots before August 20.

The Fig. 5 shows charts of estimated versus measured global solar irradiation for each condition. The best correlation among measured and estimated values was obtained with mixture ratio of 5% of black carbon. The great dispersion of the data may have been caused by several factors. For example, the mixture ratio of black carbon shows a high variability in field experiments and it can vary in different phases of the same fire event (Ferek et al., 1998). It would be necessary to apply this validation process for one complete dry season to get more clear sky days data points and to allow a more conclusive statistical analysis.

The cloud cover determination process using satellite images can be an important source of errors. The use of only three available daily satellite images (three different times per day for each day: 12UTC, 15UTC and 18UTC) to calculate the cloud cover coefficient contributes to the large dispersion of data points in Fig. 5. This limitation may somewhat masks the improvement of the new aerosol parameterization but this is a limitation of the raw satellite data availability.

In addition, smoke can be erroneously identified as clouds and, in that case, the n_{eff} value will be larger than the real value. When this error occurs, the model will miscalculate by applying two radiative processes (aerosols and clouds) when only one should be used to estimate the atmospheric transmittance. It will be necessary to develop a new methodology to discriminate clouds and smoke in satellite images in order to produce reliable cloud cover index during dry season in central north region of Brazil. Only clear sky days ($n_{eff} < 0.2$) were used in this work in order to minimize the second type of error in this work.

5. Conclusions

The validation analysis demonstrated that the new parameterization improves the reliability of solar irradi-

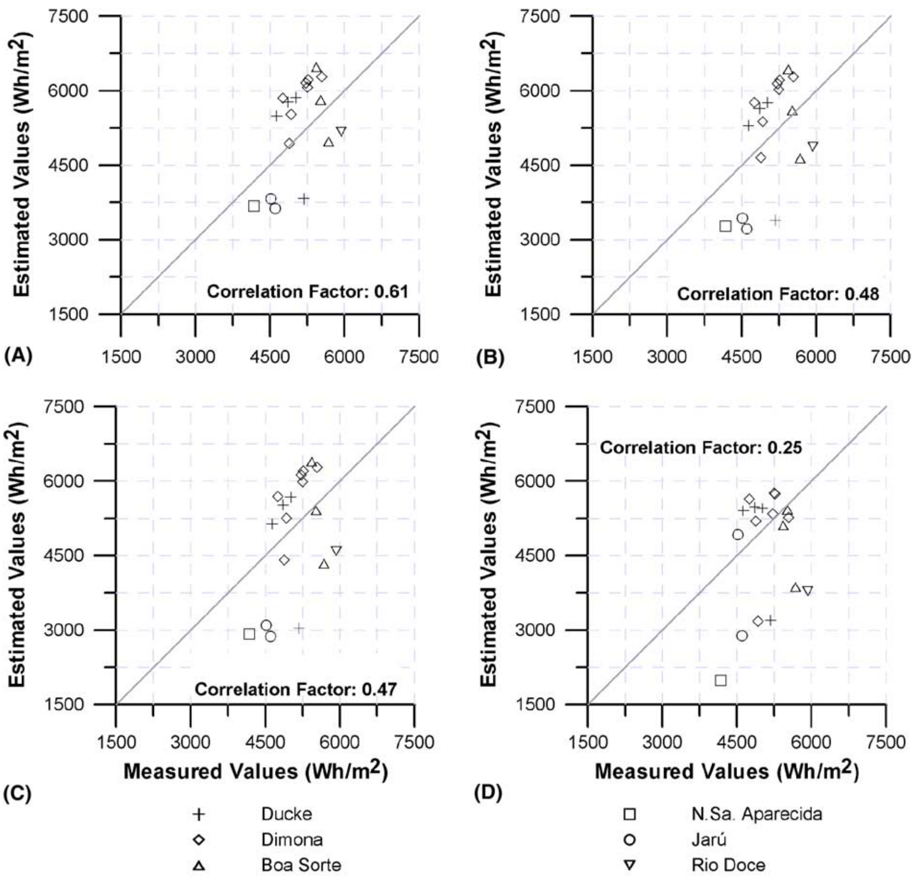

Fig. 5. Estimated versus measured values of daily global solar irradiation for different parameterizations of biomass burning aerosols: (A) black carbon ratio at 5%; (B) black carbon ratio at 7.8%; (C) black carbon ratio at 10% and (D) without biomass burning.

ation estimates by reducing the rRMSE and rMBE values. The correlation among measured and estimated values of global solar irradiation was larger when the new aerosol parameterization was applied. The best correlation coefficient was 2.5-fold larger than the correlation coefficient obtained without the new aerosol parameterization obtained for a black carbon ratio of 5%. The dispersion of data points can be linked with the high variability of black carbon ratios present in the aerosol. The BRASIL-SR model provided better solar irradiation estimates when the parameterization of aerosols is applied for Boa Sorte, Dimona and Ducke. These sites yielded the lowest rMBE and rRMSE values and presented the largest amount of clear sky days in the validation time period. Dimona site presented the larger number of clear sky days (7). The rMBE was reduced from 21% to 11% and rRMSE was reduced from 22% to 15% in Dimona when black carbon ratio equals 10% was used to parameterize aerosols from induced fires. The best result was obtained for Boa Sorte site where 3 days of clear sky occurred. The rMBE was reduced from 20% to 4% and rRMSE from 38% to 12%, when a black carbon ratio of 5% was applied. To get a more complete outlook from the benefits of new aerosol parameterization it will be necessary to apply this validation process for one complete dry season in order to yield a larger number of clear sky days for each site. New ground measurements sites are been installed in North and Central region of Brazil as part of SONDA project (www.cptec.inpe.br/sonda) and we will be able to improve the aerosol parameterization using a longer validation period in the close future. The next steps in this research will be to use aerosol profile provided by atmospheric transport models running at CPTEC/INPE routinely as input to the new aerosol modeling, and improve the cloud screening in satellite images to get more confidence in cloud cover index by discriminating clouds from smoke.

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