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Modeling of gaseous, aerosol, and cloudiness effects on surface solar irradiance measured in Brazil's Amazonia 1992–1995

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Abstract. The effects of water vapor, aerosol, and cloudiness on the incident surface solar irradiance continuously measured in Brazil's Amazonia at six observational sites from 1992 to 1995 are examined by means of a clear-sky broadband radiative transfer model. The aerosol optical depth and precipitable water, both retrieved from Sun photometer measurements, serve as inputs to the model. Computed monthly mean values of clear-sky surface irradiance are analyzed in conjunction with the monthly mean values of all-sky surface irradiance measured on the ground. To assess the effect of cloudiness, we present the cloud radiative forcing and cloud radiative forcing ratio at the surface, both widely employed in cloud radiation budget studies. By its definition the monthly mean cloud radiative forcing (cloud radiative forcing ratio) is the difference (ratio) between surface solar irradiances under all-sky and clear-sky conditions. The analysis of the irradiances, as computed and as measured, shows that during the wet season the gaseous and cloudiness effects on the solar radiation attenuation in the atmosphere are comparable, while the aerosol influence is much smaller. The aerosol effect increases and cloudiness effect decreases in the second half of the dry season. Thus during the biomass burning period in southern Amazonia, the water vapor and aerosol effects become comparable, while the cloudiness impact is 2–3 times smaller. Both cloudiness and aerosol effects have strong seasonal variations, while the gaseous effect changes slightly throughout the year.

1. Introduction

The Amazonia region of Brazil covers the basin of the Amazon river and includes nine Brazilian states having a total area 4.9 million km². It has an equatorial climate characterized by high temperatures and humidities throughout the year. Nevertheless, noticeable seasonal and interannual variations of climate are observed, particularly in its southern part. Analysis of climate variations is needed to study natural and anthropogenic impacts on climate of this unique region mainly covered by tropical rain forest. A large body of climatological

data was obtained during the Anglo-Brazilian Amazonian Climate Observation Study (ABRACOS) carried out in Amazonia from 1991 to 1993 [Gash *et al.*, 1996]. Measurements of the upward and downward radiation fluxes as well as meteorological variables were taken by automatic weather station at six observational sites: in southern Amazonia near Ji-Paraná, Reserva Jaru (RJ) (10°05'S, 61°55'W) and Fazenda Nossa Senhora Aparecida (NS) (10°45'S, 62°22'W); in eastern Amazonia near Marabá, Reserva Vale do Rio Doce (RV) (5°45'S, 49°10'W) and Fazenda Boa Sorte (BS) (5°10'S, 48°45'W); and in central Amazonia near Manaus, Reserva Ducke (RD) (2°57'S, 59°57'W) and Fazenda Dimona (FD) (2°19'S, 60°19'W). The locations of the sites shown in Figure 1 represent different climatological zones in Amazonia.

Culf *et al.* [1996] present monthly mean values of incident surface irradiance S_i , humidity e , as well as daily maximum and daily minimum surface air temperatures

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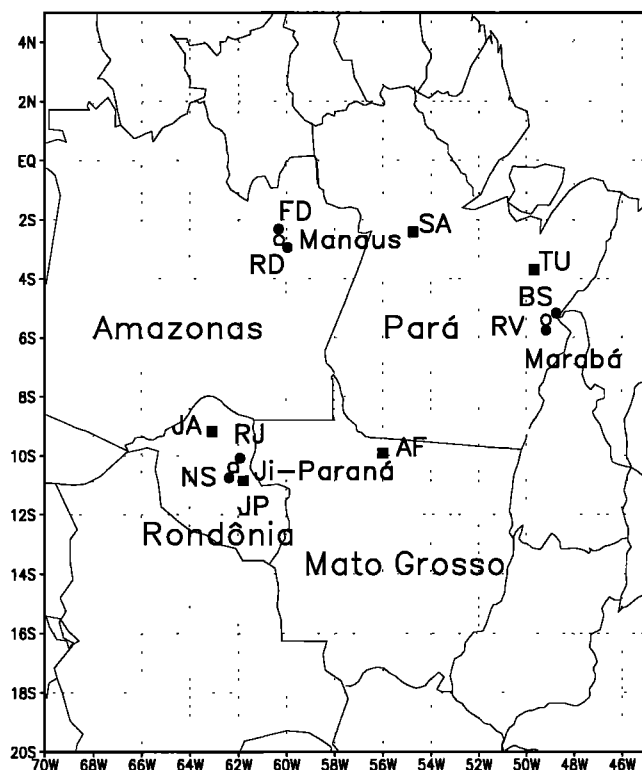


Figure 1. Observational sites in Amazonia where pyranometer measurements of ABRACOS are collected from 1991 (solid circles) and Sun photometer measurements at the AERONET global Sun photometer network were taken from 1993 to 1995 (squares). The complete names of the sites are given in the text; the scale of the map is about 340 km in 1 cm.

T_{\max} and T_{\min} , which were obtained during ABRACOS from 1991 to 1993. It is shown that the magnitude of S_i varies slightly throughout the year at all sites, elevating a little between July and October. The magnitude of T_{\min} and e has a minimum in July, while T_{\max} has a maximum between July and October. However, the causes of seasonal variations of these variables are not analyzed by Culf *et al.*, [1996]. In the present study we explore the effects of water vapor, aerosols, and cloudiness on the monthly mean incident surface irradiance by means of clear-sky radiative transfer model calculations using a larger data set obtained at the ABRACOS sites from 1992 to 1995. The relationships between the surface irradiance and the near-surface air temperature are also examined.

Water vapor, aerosols, and cloudiness are the main atmospheric components strongly influencing solar radiation transfer in the Earth's atmosphere. In Amazonia, substantial seasonal variations of precipitation, precipitable water, cloud amount, and aerosol optical depth are observed throughout a year. Thus records of the monthly mean rainfall at the standard climate stations closest to the ABRACOS sites [Gash *et al.*, 1996] show a strong change of precipitation from a wet period

between December and April to a dry period between June and August or September. Southern Amazonia has a pronounced dry season, often with a period of several weeks without rain: The rainfall decreases in Ji-Paraná to less than 5 mm in July as compared with 250 mm in March. The dry season in eastern and central Amazonia is less pronounced: The change of precipitation in Marabá is from 300 mm in February to 20 mm in July, and in Manaus it is from 300 mm in March to 90 mm in July. Satellite observations of cloudiness from 1987 to 1988 show that the monthly mean cloud amount varied in southern Amazonia from 80% in April to 15% in July [Rossow and Schiffer, 1991]. Ground-based Sun photometers at the sites of the AERONET global Sun photometer network [Holben *et al.*, 1996] record small values of column aerosol optical depth during the wet period and the elevation of its magnitude in the second part of a dry period when anthropogenic burning of savanna and forest occurs.

Such profound seasonal variations of water vapor, aerosol, and cloudiness in the tropical atmosphere of Amazonia should influence the magnitude of surface solar irradiance and, possibly, near-surface air temperature. First, we studied these effects by analyzing monthly mean values of incident surface irradiance and climatological variables obtained at the ABRACOS sites from 1992 to 1995. To estimate the atmospheric effect on the solar radiation attenuation, we computed normalized surface irradiance defined as the ratio of incident solar irradiance at the surface to that at the top of the atmosphere. To analyze the effects of precipitable water and aerosol loading on seasonal variations of normalized surface irradiance, we performed the clear-sky radiative transfer model calculations with broadband radiative transfer code. The effect of cloudiness was estimated by calculating the difference or ratio of surface solar irradiance measured under all-sky conditions and that computed by the clear-sky radiative transfer model.

2. Instrumentation and Measurements

2.1. Surface Solar Irradiance and Meteorological Variables

A detailed description of the ABRACOS observational sites can be found in the work of Gash *et al.* [1996]; however, a short summary relevant to the present study is given as follows: Measurements are made by an automatic weather station (AWS) at each site. At the Reserva Jaru (RJ), Reserva Vale (RV), and Reserva Ducke (RD) sites the AWS is mounted above the forest canopy on the top of a tower at a height of about 50 m above the ground, while at the Fazenda Nossa Senhora Aparecida (NS), Fazenda Boa Sorte (BS), and Fazenda Dimona (FD) sites, it is mounted at the heights from 2 to 5 m above the ground. The CM-5 solarimeter (Kipp and Zonen, Delft, Netherlands) measures total downward solar irradiance (300–3000 nm) at a 5 min

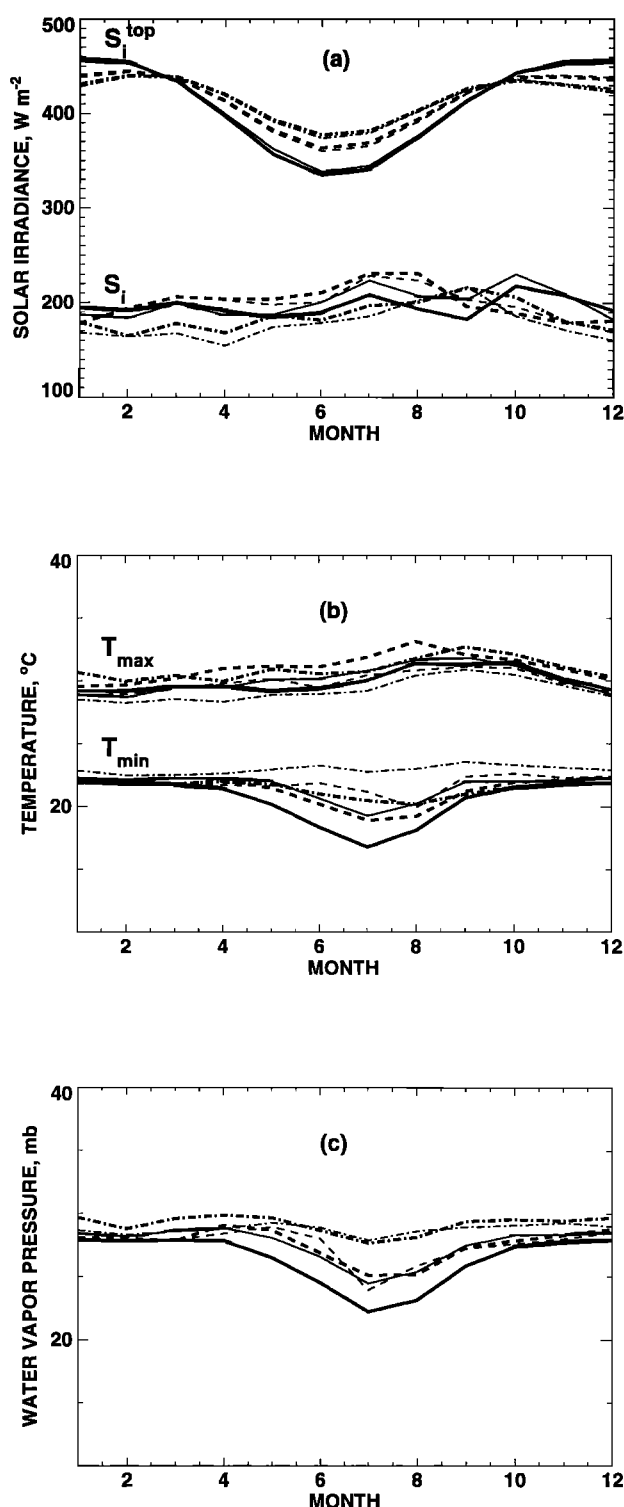


Figure 2. (a) Monthly mean solar irradiance incoming at the top of the atmosphere (S_i^{top}) and at the surface (S_i). (b) Daily minimum (T_{min}) and daily maximum (T_{max}) surface air temperatures, and (c) water vapor pressure. Measurements were taken at the ABRACOS sites: NS (thick solid) and RJ (solid) located near Ji-Paraná, BS (thick dashed) and RV (dashed) located near Marabá, and FD (thick dashed-dotted) and RD (dashed-dotted) located near Manaus. Monthly mean data are averaged over 4 years from 1992 to 1995; the values of S_i^{top} are computed.

sampling interval, which was recorded as hourly average data. The error in measured solar flux is estimated to be about $\pm(3\text{--}4)\%$ due mainly to a combination of cosine response, calibration, nonlinearity, leveling, and thermal offset errors. The near-surface air temperature and dew point temperature are measured by wet and dry bulb platinum resistance thermometers (Didcot Instrument Company, Abington, England) every 10 min with the recorded data averaged over 1 hour. These thermometers are accurate to $\pm 0.1^\circ\text{C}$.

In this study we analyze data of incident surface irradiance S_i as well as daily maximum and daily minimum surface air temperatures T_{max} and T_{min} , continuously measured at the ABRACOS sites located near Ji-Paraná (NS and RJ), Marabá (BS and RV), and Manaus (FD and RD) from 1992 to 1995. The values of water vapor pressure e , also analyzed, were computed from dew point temperature data using the Tetens formula [Tetens, 1930]. Figure 2 shows monthly mean values of S_i , T_{max} , T_{min} , and e averaged over 4 years from 1992 to 1995 as well as monthly mean values of solar irradiance incident at the top of the atmosphere, S_i^{top} . The values of S_i^{top} were computed by using the solar constant 1367 W m^{-2} [Frohlich and London, 1986] and formulas for the solar zenith angle and eccentricity correction factor of the Earth's orbit [Iqbal, 1983]. Figure 2 shows that S_i^{top} has a pronounced seasonal variation with a minimum in June related to the position of Sun-Earth relationship. Both T_{min} and e have a minimum in July with 1 month delay as compared with the minimum of S_i^{top} in June. On the contrary, both S_i and T_{max} have a maximum between July and October. Note that the delay between the annual cycle of the incoming solar irradiance and that of soil temperature, which is related to the near-surface air temperature, can be estimated by the simple model taking into account only the radiation balance at the surface and the heat conduction and heat capacity of a soil. Its value is small for dry soils and it is up to 46 days for wet soils with the high heat conduction [Khrgian, 1978].

Therefore atmospheric impact on the solar radiation transfer leads to the different annual cycles of the incident solar irradiance at the surface as compared to the top of the atmosphere and, possibly, to the different annual cycles of daily minimum and daily maximum near-surface air temperatures. The normalized surface irradiance, defined as the ratio of surface irradiance to that at the top of the atmosphere, also strongly changes throughout the year. Figure 3 shows that the magnitude of the normalized surface irradiance increases from 0.4 in January at all sites to 0.6 in July at the Ji-Paraná and Marabá sites, and to 0.5 in July at the Manaus sites. In order to estimate separately the water vapor, aerosol, and cloudiness impacts on these variations, we performed clear-sky radiative transfer model calculations using as inputs to the model the values of aerosol optical depth and precipitable water obtained from Sun photometer measurements.

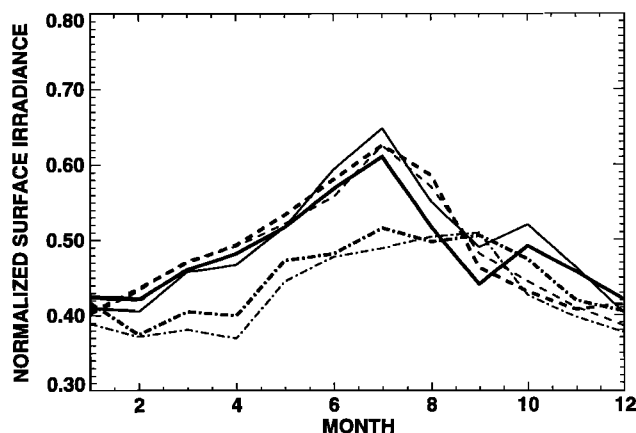


Figure 3. Monthly mean normalized surface irradiance (S_i/S_i^{top}) computed for the ABRACOS sites: NS (thick solid) and RJ (solid) located near Ji-Paraná, BS (thick dashed) and RV (dashed) located near Marabá, and FD (thick dashed-dotted) and RD (dashed-dotted) located near Manaus. Monthly mean data are averaged over 4 years from 1992 to 1995.

2.2. Aerosol Optical Depth and Precipitable Water

Figure 1 also shows the locations of the sites of the AERONET global Sun photometer network [Holben *et al.*, 1996] selected for the study. The AERONET sites closest to the ABRACOS sites near Ji-Paraná were Ji-Paraná (JP) (10°51'S, 61°47'W) and Jamari (JA) (9°11'S, 63°05'W). The nearest site to the ABRACOS sites near Marabá was Tukurui (TU) (3°42'S, 49°40'W) and to the ABRACOS sites near Manaus was Santarem (SA) (2°25'S, 54°45'W). At the AERONET sites the aerosol optical thickness was retrieved from the direct solar radiation measurements made by Cimel Sun photometers at seven selected wavelengths 340, 380, 440, 500, 670, 870, and 1020 nm, while precipitable water was derived from the measurements at 940 nm. Cloud screening was performed using the methods described by Smirnov *et al.* [1999]. The aerosol optical depth at 550 nm, τ_{550} , needed for use as input to the radiative transfer model, was computed by interpolating the values of τ_{500} or τ_{440} and τ_{670} .

The derivation of the aerosol optical thickness at 550 nm from the momentary Sun photometer measurement of the direct solar radiation is accurate to 0.02. It is more difficult to estimate the error of the monthly mean aerosol optical depth derivation because of the lack of measurements for each day of a month. Cloudiness sometimes prevents direct solar radiation measurements from being taken during a dry season period and frequently interrupts them in the wet season months. We consider monthly means to be representative for the dry season months when aerosol optical depth varies strongly if measurements are taken for more than 14 days (about half of a month) and dispersed all over a

month. This criterion could be verified with acquiring more data. Figure 4 shows for the period from 1993 to 1995 the monthly mean data of aerosol optical depth and precipitable water which meet this requirement.

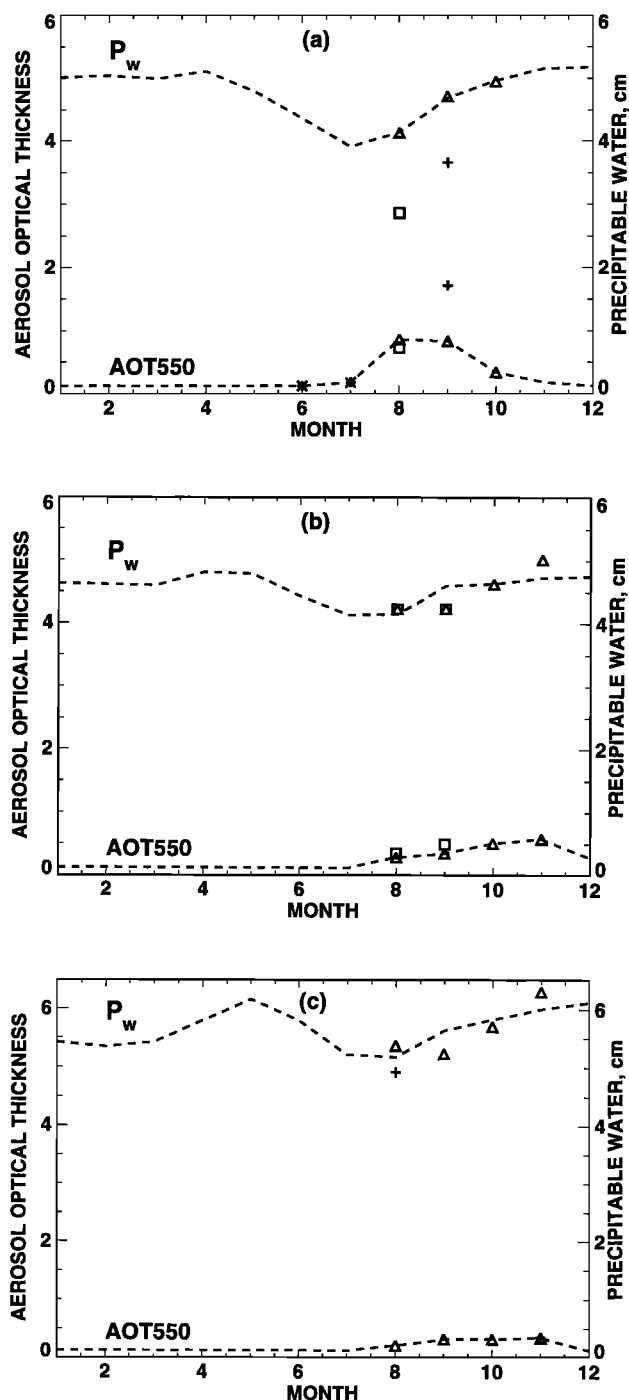


Figure 4. Monthly mean values of aerosol optical thickness at 550 nm (AOT550) and precipitable water (P_w), both obtained at the AERONET sites: (a) Jamari in 1993 (triangles), Ji-Paraná in 1994 (squares), Ji-Paraná in 1995 (pluses), Alta Floresta in 1993 (asterisks); (b) Tukurui in 1993 (triangles), Tukurui in 1994 (squares); (c) Santarem in 1993 (triangles) and Santarem in 1995 (pluses); dashed curves present assumed seasonal variations of AOT550 and P_w .

The magnitude of the aerosol optical depth in Amazonia increases in the second part of the dry season due to the smoke aerosols emitted into the troposphere by anthropogenic burning of savanna and forest. Sun photometer monthly mean data obtained at the Jamari AERONET site located 250 km northwest of Ji-Paraná can also be used to estimate the elevation of the aerosol optical depth at the Ji-Paraná ABRACOS sites in the dry season months. The assumption is based on the facts that the main biomass burning sources are located to the south from the 10°S latitude, and the primary direction of the air mass transport over the region is northwest [Trosnikov and Nobre, 1998]. The distance between the AERONET site Tukurui and the ABRACOS sites near Marabá is about 200 km and between the AERONET site Santarem and the ABRACOS sites near Manaus is about 600 km. Nevertheless, we assume that Sun photometer monthly mean data obtained in Tukurui and Santarem can be utilized to approximately estimate the elevation of the aerosol optical depth during a dry season in Marabá and Manaus, respectively, considering low spatial variability of the aerosol optical depth in eastern and central Amazonia due to the weaker biomass burning there and prevailing of the transported smoke aerosols. Note that the aerosol optical depth values obtained in Tukurui and Santarem can be more influenced by oceanic aerosols.

We also assume that the smallest monthly mean value $\tau_{550} = 0.12$ recorded at the Alta Floresta site (AF) (9°55'S, 56°00'W) in June 1993 is the maximum estimate for the wet season months in Amazonia, considering strong washout from precipitation of aerosol particles and the near absence of anthropogenic aerosol sources during the wet season. We utilized this value in the calculation for the months from December to June at all sites, bearing in mind that the real aerosol impact on the solar irradiance should be even smaller.

The elevation of the monthly mean aerosol optical depth in August, September, and October 1993, 1994, and 1995 at the AERONET sites Jamari (JA) and Ji-Paraná (JP), both located near Ji-Paraná, is shown in Figure 4a. The largest data set was obtained in 1993 at the Jamari site. In 1995 the anomalous conditions with higher temperatures, lower humidities, and more extensive biomass burning were observed in southern Amazonia. Thus the magnitude of the monthly mean aerosol optical depth at 550 nm was equal to 0.83 at the Jamari site in September 1993, and it was about 1.71 at the Ji-Paraná site in September 1995. The magnitude of the aerosol optical depth elevation in eastern and central Amazonia is smaller than in its southern part. Figures 4b and 4c demonstrate that there is an increase of τ_{550} to about 0.5 at the Tukurui site (TU) and to about 0.3 at the Santarem site (SA) in November 1993 due to the local or regional biomass burning extended to the later months in this region. The monthly mean data obtained in the 1994 and 1995 years at the Santarem and Tukurui sites do not differ much from the data obtained in 1993.

The annual cycle of precipitable water P_w , at the ABRACOS sites, is related to the annual cycle of surface humidity shown in Figure 2c and to the seasonal variations of precipitation described in section 1. Monthly mean values of P_w , obtained at the AERONET sites in 1993, 1994, and 1995, are also shown in Figure 4. In accordance with the seasonal cycles of the surface humidity and precipitation, the decrease of P_w during the dry season is more profound in southern Amazonia than in its eastern and central parts. However, Sun photometer measurements do not provide enough data to describe seasonal variations of P_w due to the lack of measurements in the wet season months. We computed monthly mean values of precipitable water for all months in 1993 from the surface water vapor pressure data using simple linear regressions obtained by fitting data of e and P_w measured simultaneously at the closest ABRACOS and AERONET sites during the dry season period. The results are shown in Figure 4 by dashed curves and are used as inputs in the clear-sky radiative transfer model.

3. Modeled Surface Solar Irradiance

A detailed description of the radiative transfer model used in the present study as well as a comparison of modeled and measured irradiances can be found in the work of Tarasova *et al.* [1999], while a short description is given as follows: The model consists of 23 homogeneous layers. The Delta-Eddington method [Joseph *et al.*, 1976] is used to calculate the solar radiative transfer in 14 intervals in the visible solar spectrum and in three bands in the near infrared. The k -distribution function [Chou and Lee, 1996] is incorporated in the near-infrared region of the spectrum, in order to compute water vapor absorption in conjunction with aerosol scattering and absorption. Both the water vapor amount vertical profile divided by the total water vapor amount in atmospheric column and the ozone amount profile are in accordance with the tropical standard atmosphere of McClatchey *et al.* [1972]. Seasonal variation of column ozone amount is not incorporated in the model because it is small in the tropics. The values of integral surface albedo measured in Amazonia by Culf *et al.* [1995] are utilized. The partition of the albedo between visible and near-infrared spectral regions was made in accordance with the data given by Briegleb [1992] for the medium/tall grassland and evergreen broad-leaved forest.

Aerosol optical parameters such as the single-scattering albedo and asymmetry factor of the phase function also required by the model, were computed for smoke aerosol composition, assuming external mixing of the components proposed by the *World Meteorological Organization (WMO)* [1986]. The composition consists of five aerosol components with the following percentages by particle volume: 71% of water soluble component, 17% of dust-like component, 7% of oceanic component, and 5% of soot component. The percentages were de-

terminated from the aerosol mass concentration measurements taken in Amazonia during the Smoke, Clouds, and Radiation-Brazil (SCAR-B) experiment [Artaxo *et al.*, 1998]. The single-scattering albedo and the asymmetry factor at 550 nm of the composition are equal to 0.866 and 0.623, respectively. Their spectral variations are given by Tarasova *et al.*, [1999]. The values of the integral surface albedo incorporated in the radiative transfer model are according to Culf *et al.* [1995]. The partitioning of the surface albedo between visible and near-infrared spectral regions was performed in accordance with the data given by Briegleb [1992] for the medium/tall grassland and evergreen broad-leaved forest.

The radiative transfer model has been tested during the SCAR-B experiment conducted in southern Amazonia in August and September 1995 [Tarasova *et al.*, 1999]. For this, six time periods of several hours were selected when simultaneous Sun photometer and solar irradiance measurements were taken at the same site in cloudless conditions. The average aerosol optical depth at 550 nm was equal to 0.34, 0.43, 0.74, 1.94, 2.14, and 2.46, precipitable water changed from 1.89 to 4.3, and solar zenith angle varied from 16° to 68°. Then the modeled and measured solar irradiances were compared. For the periods with the aerosol optical depth varied from 0.34 to 1.94 the modeled irradiances overestimate measured irradiances by 3–9%. On the contrary, for the periods with the aerosol optical depth larger than 2 the modeled total irradiance is smaller than the measured irradiance by 7–17%. By changing in the calculations the aerosol single-scattering albedo at 550 nm to 0.95 this difference can be decreased to about 1%. Thus we assume that the error of the surface irradiance calculations in cloudless conditions with the smoke aerosol optical depth at 550 nm less than 2 is less than 10%. This is comparable with currently existing discrepancies of the computations and measurements obtained under cloudless conditions by other authors [Kato *et al.*, 1997; Kinne *et al.*, 1998].

First, we calculated monthly mean values of incident surface solar irradiance S_i^{gas} for the ABRACOS sites Fazenda Nossa Senhora Aparecida (NS), Fazenda Boa Sorte (BS), and Fazenda Dimona (FD) by using the

clear-sky radiative transfer model, which includes solar radiation absorption by ozone and water vapor as well as molecular scattering. Second, the monthly mean values of incident surface solar irradiance $S_i^{\text{gas}+a}$ were computed additionally taking into account effects from scattering and absorption by aerosol particles. The solar radiation attenuation in the gaseous atmosphere is defined as the difference between the incident solar irradiance at the top of the atmosphere and that at the surface $S_i^{\text{top}} - S_i^{\text{gas}}$, while the solar radiation attenuation by aerosol particles is $S_i^{\text{gas}} - S_i^{\text{gas}+a}$. The difference between the surface solar irradiance calculated with the clear-sky radiative transfer model, which includes gaseous and aerosol attenuation, and that measured under all-sky conditions $S_i^{\text{gas}+a} - S_i$, is related to the cloudiness effect.

Table 1 presents the results of solar radiation attenuation calculations performed for the ABRACOS site Fazenda Nossa Senhora Aparecida (NS) located close to Ji-Paraná. Sun photometer data obtained in August, September, and October from 1993 to 1995 at the AERONET sites Ji-Paraná (JP) and Jamari (JA), both located near Ji-Paraná, were utilized as inputs to the model. The value of $S_i^{\text{top}} - S_i^{\text{gas}}$ is in the range from 91 W m^{-2} to 112 W m^{-2} . Its sensitivity to the magnitude of the precipitable water P_w is low. Thus the change of P_w from the value 4.1 obtained in August 1993 at the Jamari site to the value 2.9 measured in August 1994 at the Ji-Paraná site leads to the small difference 5 W m^{-2} in the magnitude of solar radiation attenuation. The solar radiation attenuation $S_i^{\text{gas}} - S_i^{\text{gas}+a}$ by smoke aerosol in Ji-Paraná is more variable. It changes from 33 W m^{-2} in October 1993 to 67 W m^{-2} in August 1993 and to 94 or 125 W m^{-2} in September 1995. The last value was computed with changed aerosol single-scattering albedo at 550 nm to 0.95, which gives better agreement with solar irradiance measurements under huge smoke hazes with aerosol optical depth close to 2 [Tarasova *et al.*, 1999]. The cloudiness effect on the solar radiation attenuation $S_i^{\text{gas}} - S_i^{\text{gas}+a}$ is also strongly variable. During August 1993 and 1994 it is about 30 W m^{-2} . In September it varies from 55 W m^{-2} in 1993 to less than 34 W m^{-2} in 1995, and it increases to 83 W m^{-2} in October 1993.

Table 1. Attenuation of the Incident Solar Irradiance in the Atmosphere by Gases ($S_i^{\text{top}} - S_i^{\text{gas}}$), Smoke Aerosols ($S_i^{\text{gas}} - S_i^{\text{gas}+a}$), and Cloudiness ($S_i^{\text{gas}+a} - S_i$) in W m^{-2} Calculated for the ABRACOS Site Fazenda Nossa Senhora Aparecida (NS) by Using the Monthly Mean Values of Aerosol Optical Depth $\bar{\tau}_{550}$ and Precipitable Water \bar{P}_w Obtained at the Jamari (JA) and Ji-Paraná (JP) AERONET Sites Located Nearby

Site	Month	Year	Number of Days	$\bar{\tau}_{550}$	\bar{P}_w	$S_i^{\text{top}} - S_i^{\text{gas}}$	$S_i^{\text{gas}} - S_i^a$	$S_i^{\text{gas}+a} - S_i$
JA	8	1993	14	0.86	4.1	96	67	30
JA	9	1993	14	0.83	4.7	106	69	55
JA	10	1993	18	0.34	5.0	112	33	83
JP	8	1994	20	0.73	2.9	91	60	29
JP	9	1995	20	1.71	3.7	102	94/125 ^a	34/3 ^a

^aThe aerosol single-scattering albedo was changed in the calculations to $\omega_0^{550} = 0.95$.

To approximately estimate seasonal variations of surface solar irradiance at the ABRACOS sites Fazenda Nossa Senhora Aparecida (NS), Fazenda Boa Sorte (BS), Fazenda Dimona (FD), located near Ji-Paraná, Marabá, and Manaus, respectively, we prepared inputs to the

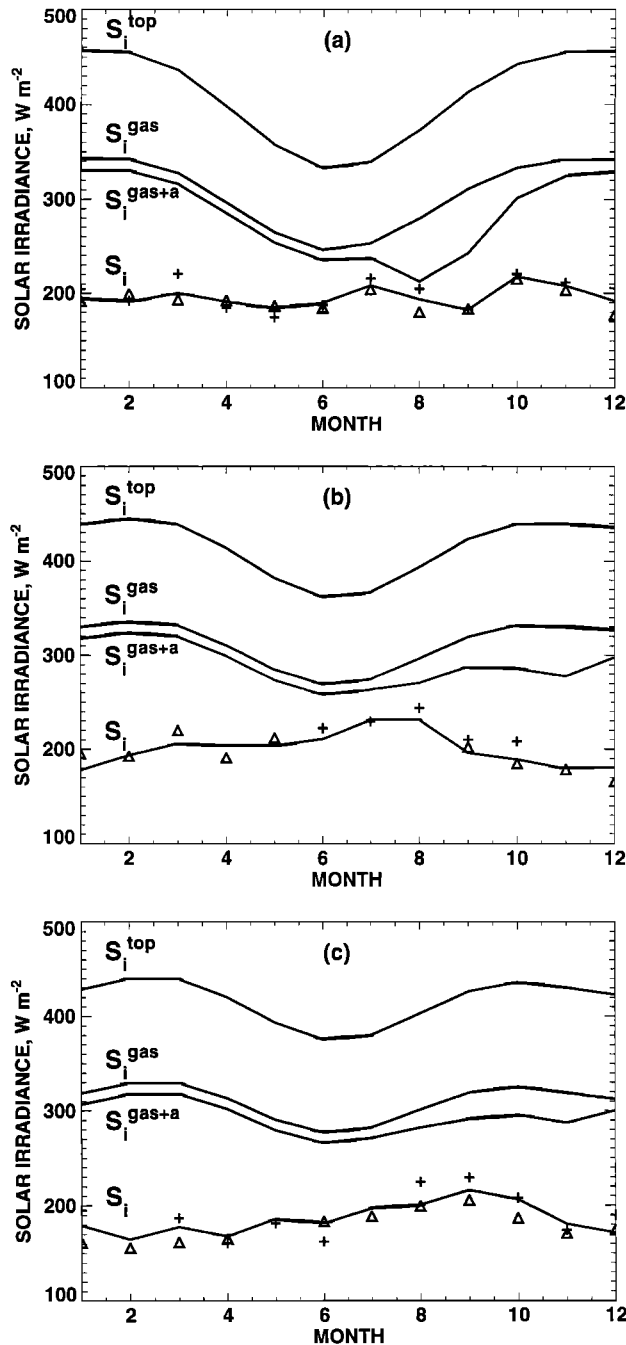


Figure 5. Monthly mean incident solar irradiances at the ABRACOS sites: (a) NS located near Ji-Paraná, (b) BS located near Marabá, and (c) FD located near Manaus. Values of S_i^{top} are computed at the top of the atmosphere; S_i^{gas} and $S_i^{\text{gas+a}}$ are computed at the surface by the clear-sky radiative transfer model for the gaseous atmosphere with and without aerosols, respectively; S_i are measured at these sites in 1993 (triangles), 1995 (pluses), and from 1992 to 1995 (solid).

clear-sky radiative transfer model for all months of the year on the basis of the data of aerosol optical depth and precipitable water, obtained at the AERONET sites Jamarí (JA), Tukurui (TU), and Santarém (SA) in 1993. The aerosol optical depth $\tau_{550} = 0.12$ was assigned to the wet months at all sites, bearing in mind to estimate the maximum aerosol effect during the wet season. These inputs are shown in Figure 4 by dashed curves, and the calculation results are presented in Figure 5. The monthly mean solar radiation attenuation by both ozone and water vapor $S_i^{\text{top}} - S_i^{\text{gas}}$ varies throughout the year in the range from 80 W m^{-2} to 110 W m^{-2} at all sites. The background atmospheric aerosols of the wet season attenuate incident solar irradiance $S_i^{\text{gas}} - S_i^{\text{gas+a}}$ by the value that is less than 15 W m^{-2} , while the aerosol impact on surface irradiance during the biomass burning period in southern Amazonia is about 70 W m^{-2} . The solar radiation attenuation by cloudiness $S_i^{\text{gas+a}} - S_i$ changes from about 120 W m^{-2} in January at all sites to about 30 W m^{-2} in August at the Ji-Paraná site. The minimum cloudiness effect on solar radiation attenuation at the Marabá site is about 30 W m^{-2} and at the Manaus site is about 80 W m^{-2} , both in July.

We also computed the normalized surface irradiance defined as the ratio of the monthly mean incident solar irradiances at the surface to that at the top of the atmosphere. Note that normalized surface irradiance is the measure of the transmissivity of the atmosphere and is equal to the transmissivity when surface albedo is equal to zero. Figure 6 shows that the magnitude of the normalized surface irradiance computed for gaseous atmosphere at all sites is about 0.75, changing slightly during the year due to water vapor variability and from site to site. Inclusion of atmospheric aerosols in the radiative transfer model calculations decreases this value to 0.7 during the wet season and to 0.57 at the Ji-Paraná site in August 1993 when biomass burning occurs. The effect of cloudiness on surface solar irradiance was estimated by computing the cloud radiative forcing ratio defined as the ratio of the incident surface solar irradiances measured under all-sky conditions (including clouds) to that calculated by the clear-sky radiative transfer model. Its magnitude varies from 0.55–0.6 in December 1993 at all sites to 0.85–0.9 in July 1993 at the Ji-Paraná and Marabá sites, presenting quite different cloudiness effects on the solar radiation attenuation in the atmosphere during the wet and dry seasons. The atmosphere in Manaus is characterized by smaller cloud radiative forcing ratio of 0.7 in July 1993 and hence by thicker cloudiness during the dry season, compared to the other two sites, which is consistent with the less profound dry season in Manaus.

4. Results and Conclusions

An analysis of surface solar irradiance data collected in Amazonia from 1992 to 1995 was performed by us-

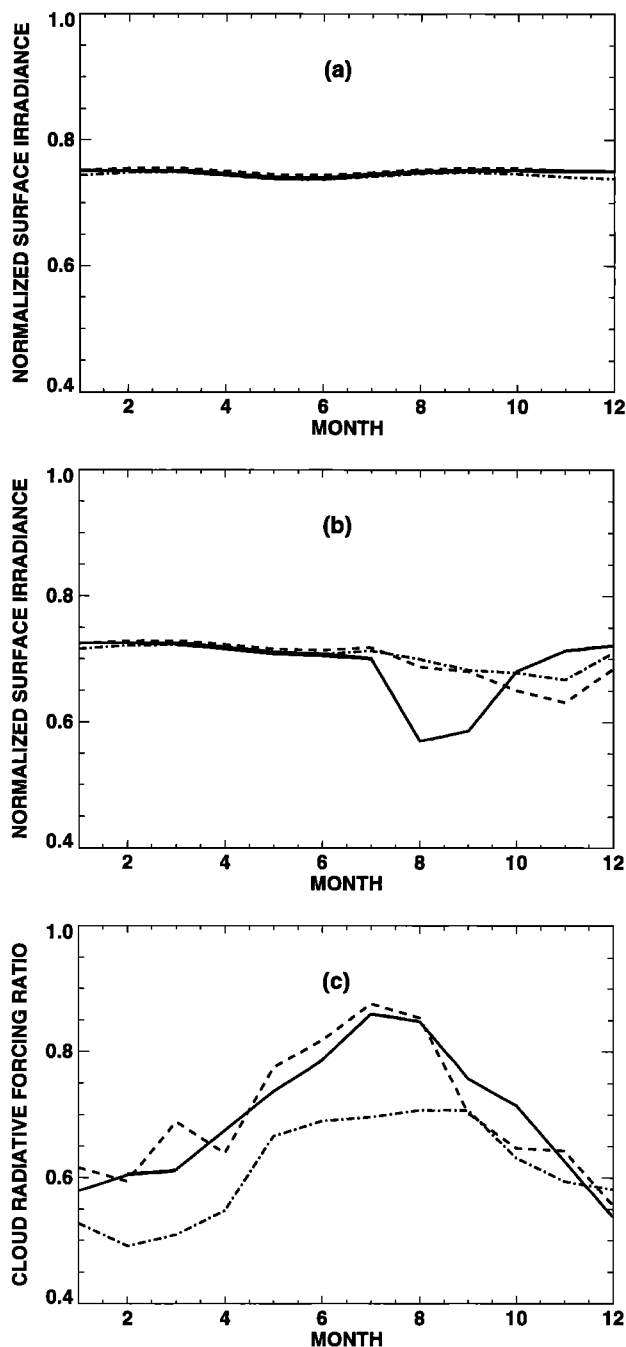


Figure 6. Monthly mean normalized surface irradiance computed for the gaseous atmosphere (a) without aerosols and (b) with aerosols. (c) Cloud radiative forcing ratio. Values were obtained for the ABRACOS sites NS (solid) located near Ji-Paraná, BS (dashed) located near Marabá, and FD (dashed-dotted) located near Manaus by using 1993 data of measurements.

ing clear-sky radiative transfer model calculations. It was shown that during the wet season the gaseous and cloudiness effects on the solar radiation attenuation in the atmosphere are comparable (about 100 W m^{-2}), while the aerosol influence is much smaller (less than 15 W m^{-2}). The aerosol effect increases and cloudiness ef-

fect decreases in the second half of the dry season. Thus during the biomass burning period in southern Amazonia the water vapor and aerosol effects become comparable (about 70 W m^{-2}), while the cloudiness impact is 2–3 times smaller. Both cloudiness and aerosol effects have strong seasonal variations, while the gaseous effect changes slightly throughout the year.

Note that the quantitative results of the study are approximate. Currently existing uncertainties in the aerosol optical parameters, either measured or modeled, cause uncertainty in the calculated surface solar irradiances. The error of the broadband radiative transfer code also contributes to it. To perform a more detailed analysis, the colocated simultaneous Sun photometer and pyranometer measurements should be taken in conjunction with in situ aerosol composition measurements. Since cloudiness in Amazonia often prevents Sun photometer measurements from being taken especially in the wet season, long-term measurements are needed to obtain representative monthly mean values of aerosol optical depth and precipitable water for each month of a year. Further improvements of solar radiation transfer codes require for comparisons more data of clear-sky surface solar irradiance, which is rarely observed in Amazonia, except at the peak of the dry season, when aerosol loading is high.

Nevertheless, results obtained in this study describe the main features of the solar radiation attenuation in the atmosphere of Brazil's Amazonia and can be used for evaluation of solar radiation fluxes simulated by general circulation and climate models under clear-sky and cloudy conditions as well as for the comparison with satellite observations of cloudiness and the radiative effects of clouds. The representativeness of the point measurements of incoming solar irradiance for their larger-scale settings are demonstrated by Wild [1999] and Bishop *et al.* [1997]. A developed approach can also be applied to any data set of direct and total solar radiation measurements obtained in various climate zones to analyze gaseous, aerosol, and cloudiness effects on the solar radiation attenuation in the atmosphere.

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