Multiyear analysis of amazonian biomass burning smoke radiative forcing of climate

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[1] Seven years analysis of clear-sky aerosol direct radiative forcing is presented for two locations in the Amazon Region heavily impacted by biomass burning emissions. During the dry season, the monthly average direct forcing at the top of the atmosphere, deduced from measurements, varied from -5 to -12 W/m^2 and at the surface from -21 to -74 W/m^2, with the difference associated with absorption of sunlight by the smoke aerosol layer. The spatial distribution of the forcings over Amazonia showed that they affect an area over 1.2–2.6 million square kilometers. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 1610 Global Change: Atmosphere (0315, 0325); 1640 Global Change: Remote sensing; 3359 Meteorology and Atmospheric Dynamics: Radiative processes. **Citation:** Procopio, A. S., P. Artaxo, Y. J. Kaufman, L. A. Remer, J. S. Schafer, and B. N. Holben (2004), Multiyear analysis of amazonian biomass burning smoke radiative forcing of climate, *Geophys. Res. Lett.*, *31*, L03108, doi:10.1029/2003GL018646.

1. Introduction

[2] Atmospheric aerosols affect climate directly, through absorption and scattering of solar radiation, and indirectly, altering clouds formation mechanisms and properties. The atmospheric radiation balance is a critical component of the Earth climate system, and an increase in atmospheric aerosol concentration causes a net change in the radiation budget, termed aerosol radiative forcing [*Kaufman et al.*, 2002; *Ramanathan et al.*, 2001a]. These changes can modify the surface temperature and thus the sensible and latent heat fluxes into the lowest layers of the atmosphere [*Yu et al.*, 2003; *Ichoku et al.*, 2003]. This causes alterations in the temperature vertical profile of the atmosphere, affecting the atmospheric stability, height of the boundary layer, regional atmospheric circulation, evaporation rate, cloud formation, and precipitation.

[3] The net effect of aerosols on climate is to cool the surface, but depending on their absorbing properties, aerosols can also warm the atmosphere while cooling the Earth surface [*Kaufman et al.*, 2002; *Ramanathan et al.*, 2001a]. The aerosol absorption properties depend mainly on the black carbon concentration, and on the internal vs. external mixing with the non-absorbing material in the particle [*Dubovik et al.*, 2002; *Jacobson*, 2001]. Aerosols from biomass burning contain high concentrations of black carbon, nevertheless the scattering of light is predominant in the smoke particles, as can be seen from the magnitude of the measured [*Dubovik et al.*, 2002] and calculated [*Procopio et al.*, 2003] smoke single scattering albedo.

[4] The Amazon region has been experiencing a large number of forest fires in the past years, mainly in the peak of the dry season (from August to October), with a considerable increase in the atmospheric aerosol loading. The aerosol optical thickness at 500 nm (τ_a) measured by AERONET sunphotometers [*Holben et al.*, 1998] reaches values as high as 4 during this period in Amazonia; just for comparison, the wet season τ_a regional climatological average is 0.10. Occasionally relatively high values of τ_a are observed in the Arch of Deforestation Region during the wet season as well, due to some year round burning activities in this area, especially from the lumber industry and domestic cooking.

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Table 1. Regression Coefficients for the Aerosol Radiative Forcing at the Surface and Top of Atmosphere (TOA)

$^{a}ARF_{24h} = a(\tau_a)^3 + b(\tau_a)^2 + c\tau_a + d$					
	a	b	c	d	R^2
surface	0	5.04	-51.6	3.92	0.999
TOA	-0.95	6.71	-16.5	1.57	0.994

$^{a}ARF_{24h}$ is the 24 h aerosol radiative forcing (Wm^{-2}), τ_a is the daily average aerosol optical thickness (at 500 nm), and a, b, c and d are regression coefficients.

[5] The objective of this study is to obtain the direct radiative forcing of the smoke aerosols at the top of atmosphere, at the atmosphere and at the surface for a long time period in the Amazon Basin using τ_a obtained by AERONET, as well as to obtain its spatial distribution using τ_a obtained by MODIS [*Kaufman et al.*, 1997; *King et al.*, 1999]. These values are important for weather forecast and for providing a way to better understand the Amazonian ecosystem functioning under anthropogenic influences [*Artaxo et al.*, 2001; *Andreae et al.*, 2002].

2. Methodology

[6] The clear-sky direct aerosol radiative forcing (ARF) is defined here as the difference between the net solar flux (difference between downward and upward fluxes) for a certain τ_a (at 500 nm) and for τ_a representing the atmospheric background condition (0.11 at 500 nm). Generally, aerosol radiative forcing is defined as the difference between net fluxes calculated with and without aerosol loading in the atmosphere. However, aerosols are always present in the atmosphere and this former definition will slightly overestimate the effects of an enhancement of aerosols on climate, since it includes the natural aerosol on its calculations. The assumption of a background condition may be the best way to estimate the impacts of aerosols on climate owing only to the increase of τ_a due to anthropogenic activities. The value of τ_a representing the background aerosol during the wet to dry seasons transition period, 0.11 ± 0.06 (average ± sample standard deviation), was obtained from AERONET measurements at the Amazonian sites during June (1999–2002).

[7] The fluxes were calculated for the solar spectrum (0.25μm–3.60μm) by means of SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer) [*Ricchiazzi et al.*, 1998] with a temporal resolution of five minutes, for vegetated surface [*Reeves et al.*, 1975] for 14 values of τ_a (0.10 to 3.00), using the modeled spectral optical properties for smoke areosols in Amazonia calculated in *Procopio et al.* [2003]. This dynamic spectral aerosol model was developed from measurements obtained from sun photometers in Brazil during the dry season, and describes the aerosol optical properties for 12 intervals of aerosol optical thickness in 24 wavelengths in the spectral range of 0.20–3.00 μm. In the visible spectrum the single scattering albedo varies from 0.94 to 0.86, and the asymmetry factor varies from 0.69 to 0.52. The latitude of 5°S and the Julian day 258 were assumed in the calculations, representing the average latitude of the Amazon Region and the middle of the dry season, respectively. In this case, the solar declination (δ) is 3.4° (very near the autumnal equinox) and the solar zenith angle at 12:00 h (θ_{0-12h}), local time, is 1.62°. The seasonal variability of the solar declination will not significantly affect the intensity of the incident solar radiation, due to the low values of the Amazonian latitudes.

[8] Sensitivity tests concerning the effect of surface albedo on ARF_{24h} were made assuming one surface totally covered by vegetation (V), one with 80% of vegetation and 20% of sand [*Staetter and Schroeder*, 1978] (VS1), and another one with 50% of vegetation and 50% of sand (VS2). For $\tau_a = 1.00$ (at 500 nm) the calculated ARF_{24h} at the surface and at the top of atmosphere were, respectively, -42.6 and -9.2 Wm^{-2} (V), -43.2 and -10.0 Wm^{-2} (VS1), -43.8 and -11.2 Wm^{-2} (VS2). Although the sand reflectance in the visible (0.40–0.70 μm), 0.133 on average, is higher than the vegetation reflectance, 0.110 on average, the small difference found between the calculated ARF_{24h} for the three cases is associated with the high reflectance of the vegetation in the near infrared (0.70–1.30 μm), average of 0.510, compared to the sand, average of 0.312. Based on this analysis, the ARF_{24h} parameterization was obtained for a vegetated surface, meant to represent the whole Amazon region, which is in fact mostly covered by forested vegetation.

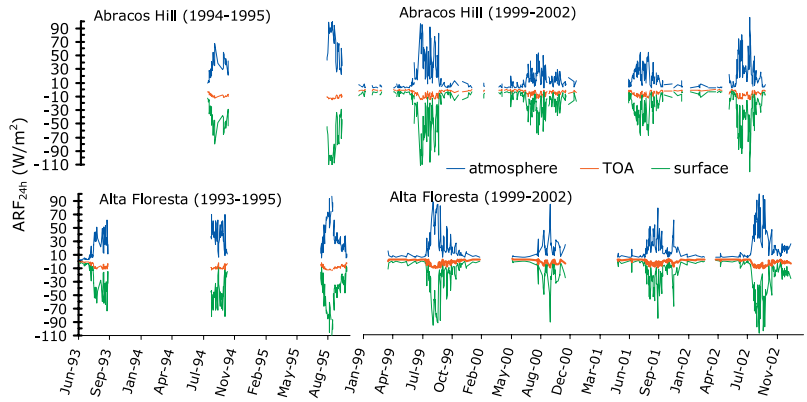

Figure 1. Seven years analysis of 24 h aerosol radiative forcing. The radiative forcing at the atmosphere (blue), top of atmosphere (red) and surface (green) in Abracos Hill (top panel) and Alta Floresta (bottom panel) were calculated with equation 1. The aerosol optical thicknesses were obtained from AERONET network data, and note that there were no measurements made from 1996 to 1998.

Table 2. Dry Season Averages of Aerosol Radiative Forcing (ARF_{24h}) at the Top of Atmosphere (TOA), at the Surface and at the Atmosphere Calculated With Equation 1 and AERONET Averages of Aerosol Optical Thickness (τ_a) at 500 nm, for Alta Floresta and Abracos Hill

			ARF_{24h} (Wm^{-2})			
location	year	τ_a (500 nm)	TOA	surface	atmosphere	heating rate (K/day)
Alta Floresta	1993	0.71	-7.1	-30.2	23.1	0.20
09°55′S	1994	1.15	-10.0	-48.8	38.8	0.33
56°00′W	1995	1.29	-10.6	-54.3	43.7	0.38
	1999	0.88	-8.4	-37.6	29.2	0.25
	2000	0.55	-5.6	-22.9	17.3	0.15
	2001	0.61	-6.2	-25.7	19.5	0.17
	2002	1.14	-9.9	-48.4	38.4	0.33
Abracos Hill	1994	1.10	-9.7	-46.7	37.0	0.32
10°45′S	1995	1.83	-12.0	-73.6	61.7	0.53
62°21′W	1999	1.02	-9.3	-43.5	34.2	0.29
	2000	0.52	-5.3	-21.5	16.2	0.14
	2001	0.60	-6.1	-25.2	19.1	0.16
	2002	0.83	-8.0	-35.4	27.4	0.24

The last column shows the smoke induced atmospheric heating rate.

[9] The resulting 24-h averaged ARF was parameterized as a function of τ_a as:

$$\mathrm{ARF}_{24h} = a(\tau_a)^3 + b(\tau_a)^2 + c\tau_a + d \quad (1)$$

where τ_a is the daily average aerosol optical thickness (at 500 nm), a, b, c and d are regression coefficients, which differ for the surface and top of atmosphere (TOA) (see Table 1). The ARF_{24h} integrated over the atmosphere can be obtained simply subtracting ARF_{24h} at the TOA from ARF_{24h} at the surface. The errors in the forcing calculations due to aerosol model uncertainties for $\tau_a = 1.0$ are ±4% for surface and ±6% for TOA.

3. Some Applications

[10] In order to assess the long time series of ARF_{24h} (Figure 1), equation 1 was applied to the daily averages of τ_a obtained from seven years AERONET measurements at Abracos Hill (10°45′S, 62°21′W) and Alta Floresta (09°55′S, 56°00′W). These two sites are approximately 700 km apart, but the corresponding dry seasons monthly averages of τ_a are correlated to each other, indicating the occurrence of a regional biomass burning impact. During these months, the average forcing at TOA varied from -5 to -12 Wm^{-2} and at the surface from -21 to -74 Wm^{-2}, with the difference associated with absorption by the smoke aerosol layer from 16 to 62 Wm^{-2}. This atmospheric forcing is equivalent to a smoke induced tropospheric heating rate of about 0.14 to 0.53 K/day, for aerosols distributed homogenously in an atmospheric layer of 1.6 km of altitude. The strongest aerosols effects were observed in 1995, 1999 and 2002, due to higher values of τ_a caused by more intense fire activities. Detailed dry season results are given in Table 2. The wet season average τ_a at these sites was 0.15, resulting in an average ARF_{24h} at the surface of -3.8 Wm^{-2}, at TOA of -0.8 Wm^{-2} and at the atmosphere of 3.0 Wm^{-2}.

[11] Equation 1 was applied to 2002 satellite data to assess large area forcings (Table 3), using τ_a derived by MODIS (level 3 data), on the TERRA platform. The monthly average area covered with smoke of optical thickness of 0.2 and higher was calculated, together with its corresponding ARF_{24h}. The forcing was calculated by applying the monthly weighted average τ_a in a box delimited by 0°–20°S and 45°–65°W. The average forcing increased from -2.7 to -6.0 Wm^{-2} (at TOA), and from -11 to -25 Wm^{-2} (at the surface), from July to September, due to increase in the atmospheric aerosol concentration. The area affected by the forcings increased from 1.3 to 2.6 million km^2 from July to September, and went down back to 1.1 million km^2 in December. Note that MODIS observes aerosol only in cloud free area on 1° latitude by 1° longitude resolution, and do not retrieve τ_a greater than 3. The large Amazonian area affected by the forcings is similar to other places in the world, as Africa [*Bergstrom et al.*, 2003; *Keil and Haywood*, 2003; *Ichoku et al.*, 2003] and South and East Asia [*Ramanathan et al.*, 2001b; *Satheesh and Ramanathan*, 2000], for example.

[12] The mean forcing found with this parameterization for $\tau_a = 1$ (at 500 nm) is -43 Wm^{-2} at the surface and -9 Wm^{-2} at TOA, with 34 Wm^{-2} absorbed in the atmosphere by the smoke layer. For comparison, *Ross et al.* [1998] reported forcings at TOA for the 1995 dry season in Amazonia ranging from -8 ± 9 Wm^{-2} to -20 ± 7 Wm^{-2}. Unfortunately, the uncertainty associated with the smoke ARF_{24h} is very diffi-

Table 3. Aerosol Radiative Forcing (ARF_{24h}) at the Top of Atmosphere (TOA) and Surface Calculated With Equation 1 and MODIS aerosol optical thickness ($\tau_a \geq 0.20$) from July to December (2002)

			ARF_{24h} (Wm^{-2})		
Amazon Region	month year	τ_a (500 nm) (*weighted average*)	TOA	surface	affected area (10^6 km^2)
lat: 0–20°S	July 2002	0.29	-2.7	-10.6	1.30
lon: 45–65°W	August 2002	0.51	-5.2	-21.1	2.41
total area:	September 2002	0.59	-6.0	-24.8	2.62
4.56×10^6 km^2	October 2002	0.47	-4.8	-19.2	2.43
	November 2002	0.46	-4.7	-18.7	1.84
	December 2002	0.36	-3.5	-14.0	1.12

The affected areas do not include cloudy area and area for which τ_a is not derived by MODIS ($\tau_a \geq 3$).

cult to estimate due to a limited number of available studies, as pointed out in a recent report [*Ramaswamy et al.*, 2001].

4. Concluding Remarks

[13] It was shown that the ARF_{24h} in Amazonia is very high for long periods of the year over large areas, with potential consequences to regional climate. The forcing at TOA is a small number when compared to the surface and atmospheric forcings, due mainly to the aerosol solar absorption in the atmosphere. The increase in the atmospheric heating can enhance the atmospheric stability, weaken the turbulence and convection at the atmosphere, and augment the drought condition during those periods, probably affecting the regional circulation and the Amazonian hydrological cycle. The surface forcing (i.e., cooling) can be possibly balanced by a reduction in evaporation, therefore decreasing precipitation and affecting the water budget. Additionally, albeit the reduction of global solar radiation at the surface due to the injection of smoke particles in the atmosphere, the increase in the diffuse component can enhance the canopies photosynthesis [*Gu et al.*, 2003]. The aerosol effects on climate and ecosystem functioning are very complex and involve many components of the surface-atmosphere system, and still need to be studied more carefully to answer all raised topics. The parameterization of the forcings presented in this work is a good tool to help in the accomplishment of an accurate evaluation of these effects.

[14] This was the first study of a long time series of clear-sky 24-h aerosol radiative forcing at the surface, TOA and atmosphere in Amazonia, quantifying large values occurring during long periods. The assessment of the ARF_{24h} can be made continuously with the parameterization given here, since it depends only on the aerosol optical thickness obtained through remote sensing techniques. The next step of this work is to quantify the aerosol direct forcing in cloudy skies. Clouds have an important role in the radiation budget, and for absorbing aerosols they may possibly change the sign of ARF_{24h} at TOA, from cooling under clear skies to heating under overcastting skies.

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