

# Estimation of aerosol transport from biomass burning areas during the SCAR-B experiment

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**Abstract.** A transport model for the estimation of tracers spreading from biomass burning areas has been developed on the basis of the semi-Lagrangian technique. The model consists of a three-dimensional Lagrangian form transport equation for tracers and uses the quasi-monotone local cubic-spline interpolation for calculation of unknown values at irregular points. A mass-conserving property of the model is based on the flux-corrected transport method using the algorithm of Priestley. The transport of the smoke particles from Amazonia was simulated for the period from August 20 to 29, 1995. During this period the air mass located below 2 km moved to the south and carried the smoke particles until 30°S.

## 1. Introduction

The Smoke, Clouds, and Radiation - Brazil (SCAR-B) experiment was conducted in central Brazil and the southern Amazon Basin from August 15 to September 20, 1995, in collaboration with U.S. and Brazilian agencies and academic institutions [McDougal, 1995]. The aim of the experiment was to study the properties of aerosol and the effects of biomass burning on regional and global climate, including estimation of the emission product transport. In this study a numerical transport model has been developed on the basis of semi-Lagrangian technique [Staniforth and Côté, 1991] to estimate the dispersion of gas and aerosol emissions from an area with intense biomass burning. The model has been used for the estimation of aerosol transport during the SCAR-B experiment.

## 2. Model

The model is based on the three-dimensional Lagrangian form transport equation for tracers [Brasseur and Madronich, 1992]:

$$\frac{d\chi}{dt} = D_{\chi} + \frac{S_{\chi}}{\rho}, \quad (1)$$

where  $d/dt$  is the material derivative,  $\chi = \frac{p_{\chi}}{\rho}$  is the mixing ratio of the tracer with mass density  $\rho_{\chi}$ ,  $\rho$  is the air mass density,  $D_{\chi} = K_H \nabla^2 \chi$  is the term of horizontal macrodiffusion,  $K_H$  is constant, and  $S_{\chi}$  is the source term (expressed in mass per unit volume and time). This includes both positive and negative contributions. The lateral boundary conditions for equation (1) are

taken to be  $\chi = 0$  for boundary points with an influx of air.

For the integration of equation (1) the semi-Lagrangian technique is used. Every time step consists from two stages. The first stage is to find a solution of the trajectory problem: determine the departure points at time  $t - \Delta t$  for arrival points of regular mesh at time  $t$  by using the known fields for these instants. They are determined by a solution of the system of the equations

$$\frac{dx}{dt} = u, \quad \frac{dy}{dt} = v, \quad \frac{dz}{dt} = w - v_{sed} \quad (2)$$

with the conditions

$$x(t) = x_a, \quad y(t) = y_a, \quad z(t) = z_a \quad (3)$$

where  $u$ ,  $v$ ,  $w$  are the zonal, meridional, and vertical components of the wind velocity,  $v_{sed}$  is velocity of the sedimentation of the aerosol particles, and  $x_a, y_a, z_a$  are the regular mesh coordinates (arrival point). The system is integrated backward in time by the Crank-Nicolson scheme [Williamson and Rash, 1989]:

$$x_d(t - \Delta t) = x_a(t) - \frac{\Delta t}{2}(u_a(t) + u_d(t - \Delta t)), \quad (4)$$

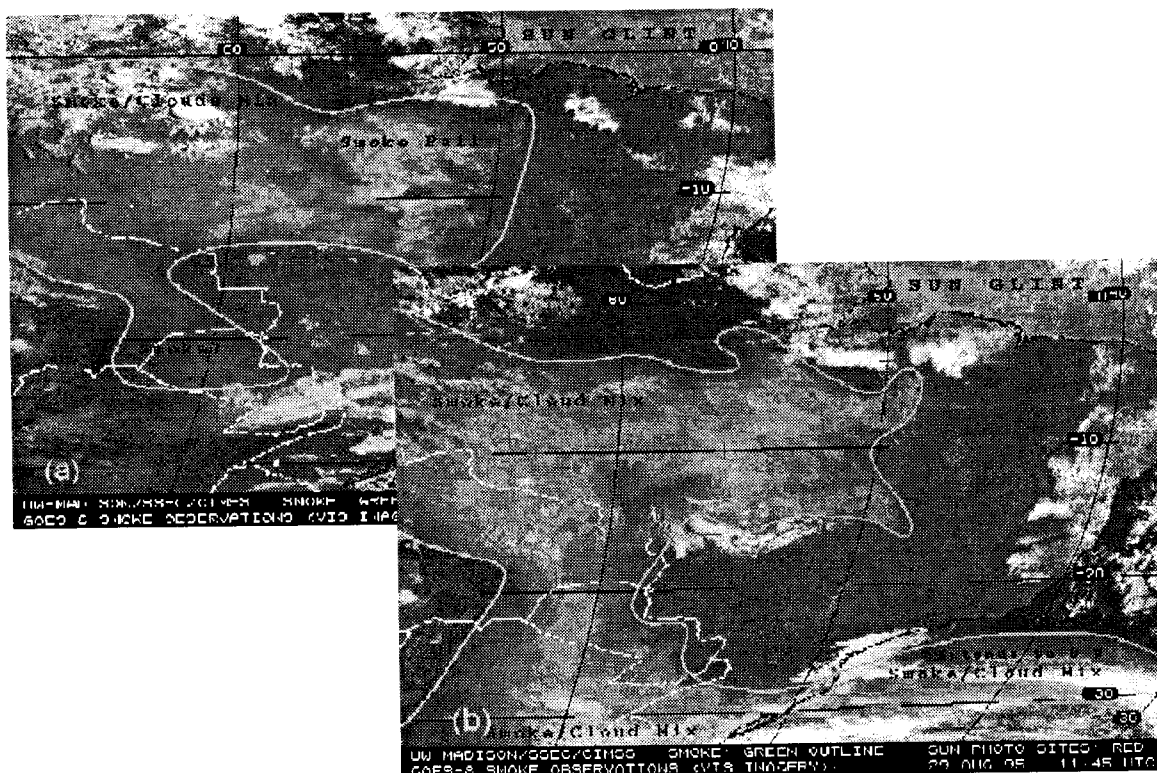
where  $\Delta t$  is a time step. The  $a$  index indicates known values,  $d$  index indicates unknown values which are determined by iterations. The same equations are integrated for  $y$  and  $z$ . The second stage consists of computations of the values of tracers on departure points and the sources of tracers on arrival points:

$$\chi_a(t) = \chi_d(t - \Delta t) + \Delta t \left( D_{\chi,a}(t - \Delta t) + \frac{S_{\chi}}{\rho} \right). \quad (5)$$

The unknown wind components and the values of tracers for the departure points are obtained by the quasi-monotone local cubic-spline interpolation (see [Bermejo and Staniforth, 1992]). If a departure point is out of the integration area of the model, the boundary

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**Figure 1.** GOES-8 visible image of smoke concentration (a) at 1145 UTC, August 20, 1995, and (b) at 1145 UTC, August 29, 1995.

values are used. The value of the tracer is set equal to zero for arrival points located below the surface of the Earth.

### 3. Conservation

A conservation algorithm has been designed by using ideas from the flux-corrected transport (FCT) method [Priestley, 1993]. The solution of the transport equation for each point with index  $k$  is obtained from two approximations of the solution at the new time level, the high-order solution,  $\chi_k^H$ , obtained by cubic interpolation, and the low-order solution,  $\chi_k^L$ , obtained by linear interpolation,

$$\chi_k^M = \alpha_k \chi_k^H + (1 - \alpha_k) \chi_k^L \quad (6)$$

$$0 \leq \alpha_k \leq 1 \quad (7)$$

where  $\alpha_k$  are to be chosen such as to make the conservative scheme for volume  $V$

$$\int_V \chi^M(t) \rho(t) dx dy dz = C \quad (8)$$

where value  $C$  includes the three terms

$$C = C_1 + C_2 + C_3 \quad (9)$$

$C_1$  is the aerosol mass for the time moment  $t - \Delta t$ ,  $C_2$  and  $C_3$  are the aerosol mass injected in the atmosphere

by sources and the aerosol flux through the lateral boundary consequently on the time interval  $(t - \Delta t, t)$ :

$$C_1 = \int_V \chi^M(t - \Delta t) \rho(t - \Delta t) dx dy dz \quad (10)$$

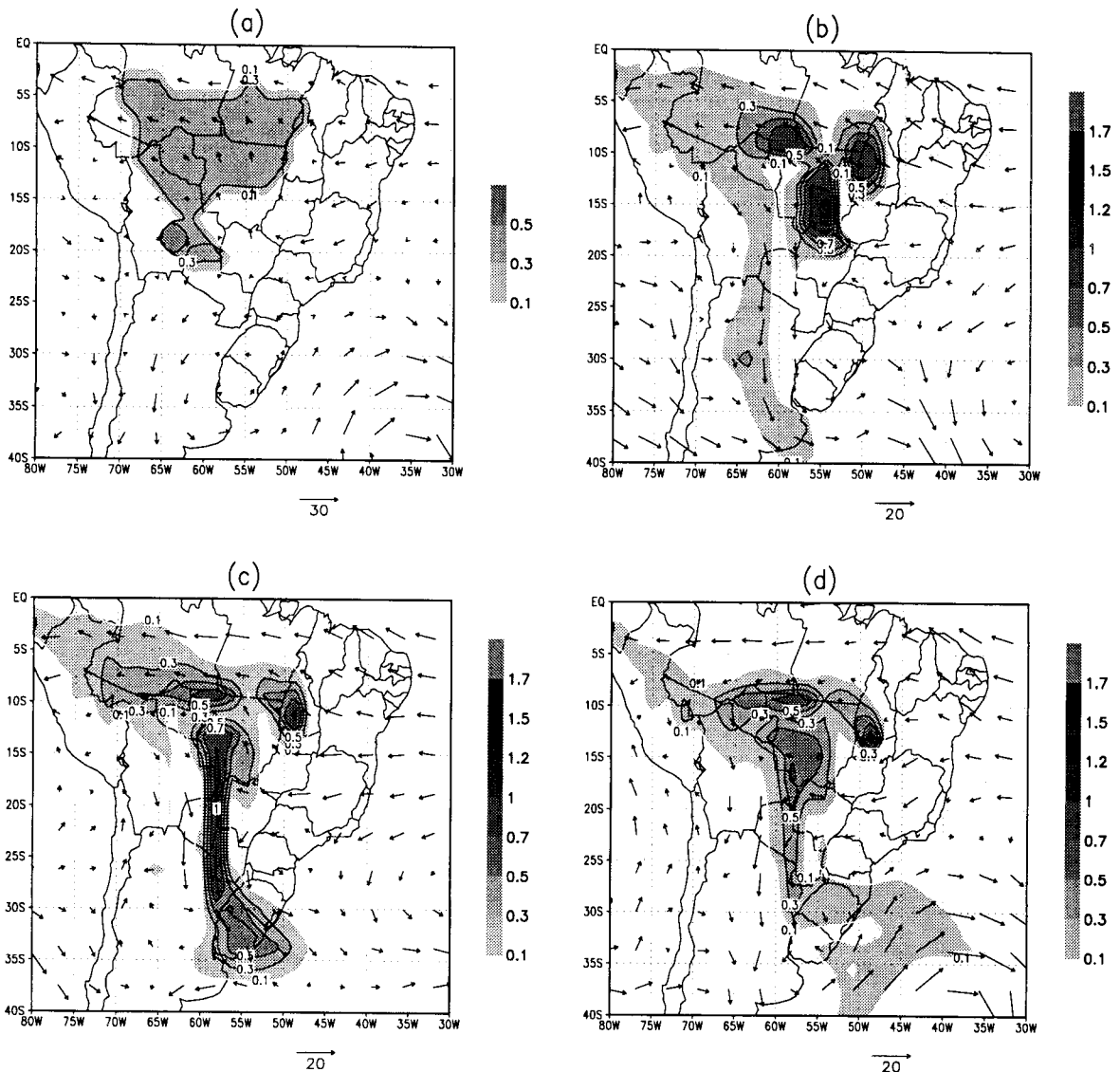
$$C_2 = \Delta t \int_V S_\chi dx dy dz \quad (11)$$

$$C_3 = \Delta t \int_\Omega \rho \chi^M(t - \Delta t) \mathbf{n} \cdot \mathbf{v}(t - \Delta t) d\Omega, \quad (12)$$

$\mathbf{n}$  is the inside normal to the lateral boundary  $\Omega$ . When the sources and flux through the lateral boundary are absent, the mass of aerosol is conservation value. The Priestley algorithm is used for determination of  $\alpha_k$  by minimization of the difference between  $\chi^M$  and  $\chi^H$  with condition (8).

### 4. Simulation of Aerosol Transport for SCAR-B Experiment

For the simulation of aerosol transport, the analysis fields of the wind, temperature, and geopotential height produced by the CPTEC global numerical weather forecast model and available from SCAR-B database were used. The grid of the analyses has 49 x 41 points with a horizontal resolution of 1.875° x 1.875° and covers South America from 101.25°W to 26.25°W and from 60°S to 15°N. The transport model has the horizontal grid colo-



**Figure 2.** Simulated aerosol concentration (arbitrary units) and wind ( $\text{m s}^{-1}$ ) at 850 hPa: (a) August 20, 1995 (initial condition); (b) August 23, 1995; (c) August 26, 1995; (d) August 29, 1995.

cated with the analyses grid, and its vertical structure includes 22 pressure levels from 1000 to 200 hPa, 16 of which are placed in the layer 1000-700 hPa. The time integration of the model was carried out with a 1 hour time step, and hourly values of the meteorological elements were calculated by linear interpolation.

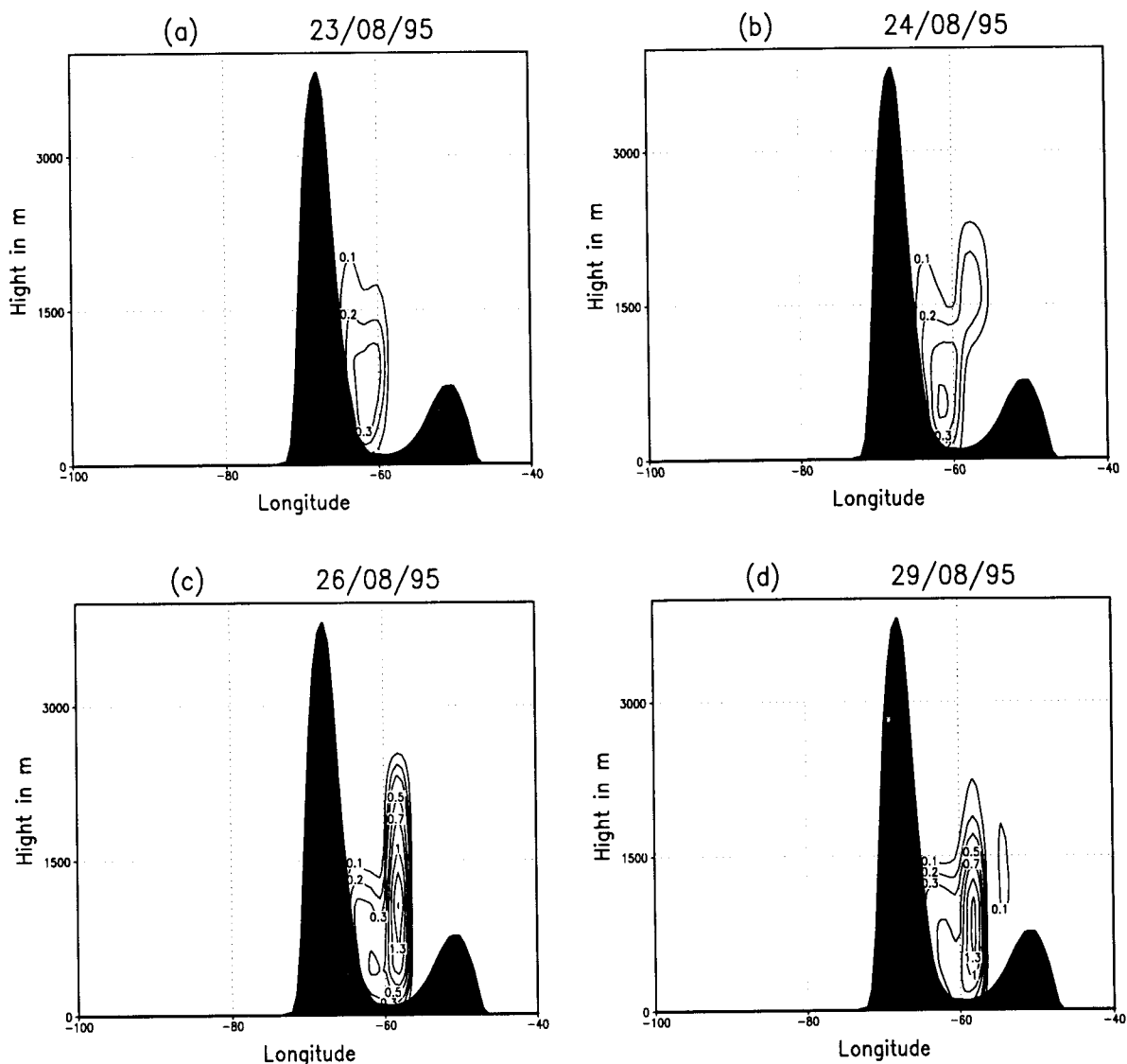
#### 4.1. Location of Aerosol Sources in Separate Regions

The sources of the aerosol  $S(x, y, z)$  were set in the grid points and were defined by two parameters: the intensity of the aerosol injection to the atmosphere  $S_0$  ( $\text{g m}^{-2} \text{s}^{-1}$ ) and the total thickness of the source layer  $\Delta P$  (hPa). The simple vertical change source model was used:

$$\frac{S}{\rho} = \frac{gS_0}{100\Delta P}, \quad (13)$$

where  $\Delta P$  is the thickness of the air layer with the source in hPa, and  $g$  is the gravitational acceleration. The choice of  $\Delta P$  for numerical experiments was determined by SCAR-B data, which shows layers of high aerosol concentrations at 1800-2500 m altitude [Artaxo *et al.*, 1996].

The aerosol measurements during the SCAR-B experiment show that aerosol particles have a size distribution with a mass peak at about  $0.3 \mu\text{m}$  diameter [Artaxo *et al.*, 1996]. It allows one to use the bulk representation of aerosol particles for transport calculations as the first approximation. The velocity of the sedimentation was taken to be  $0.001 \text{ ms}^{-1}$  [Penner *et al.*, 1991a] according to this approximation. Because the calculations were carried out for a dry season, wet scavenging is not included in the source.



**Figure 3.** Simulated aerosol concentration cross section (arbitrary units) along 25°S: (a) August 23, 1995; (b) August 24, 1995; (c) August 26, 1995; (d) August 29, 1995.

The preliminary computations showed that the term of horizontal macrodiffusion in equation (1) leads to a marked increase of the aerosol spreading area. For this reason the simulation of aerosol transport for the SCAR-B experiment was conducted with  $K_H = 0$ .

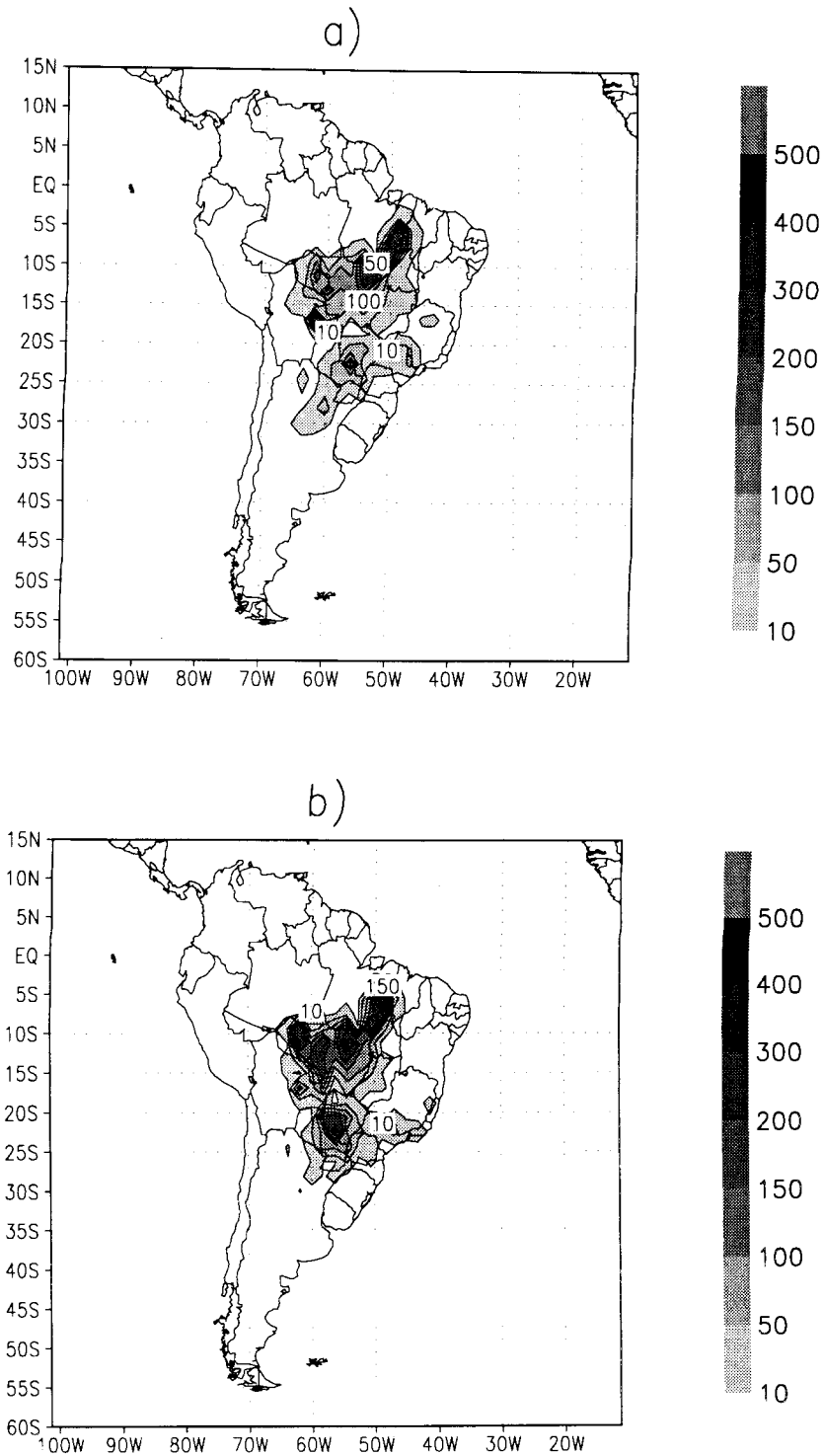
In the first numerical experiments the following source parameters were used:  $\Delta P = 162.5$  hPa or the source height was about 1500–2000 m,  $S_0 = 7.5 \times 10^{-6}$  g m $^{-2}$  s $^{-1}$ .

To link  $S_0$  with  $S_f$ , the intensity of the aerosol injection to the atmosphere from a fire territory with the area  $A_f$ , the relation

$$S_0 A_g = S_f A_f \quad (14)$$

can be used, where  $A_g$  is the model grid cell area. For example, for  $S_f = 0.003$  g m $^{-2}$  s $^{-1}$  [Penner *et al.*, 1991b] and  $A_g = 41500.0$  km $^2$ , the fire area is  $A_f = 103.8$  km $^2$ .

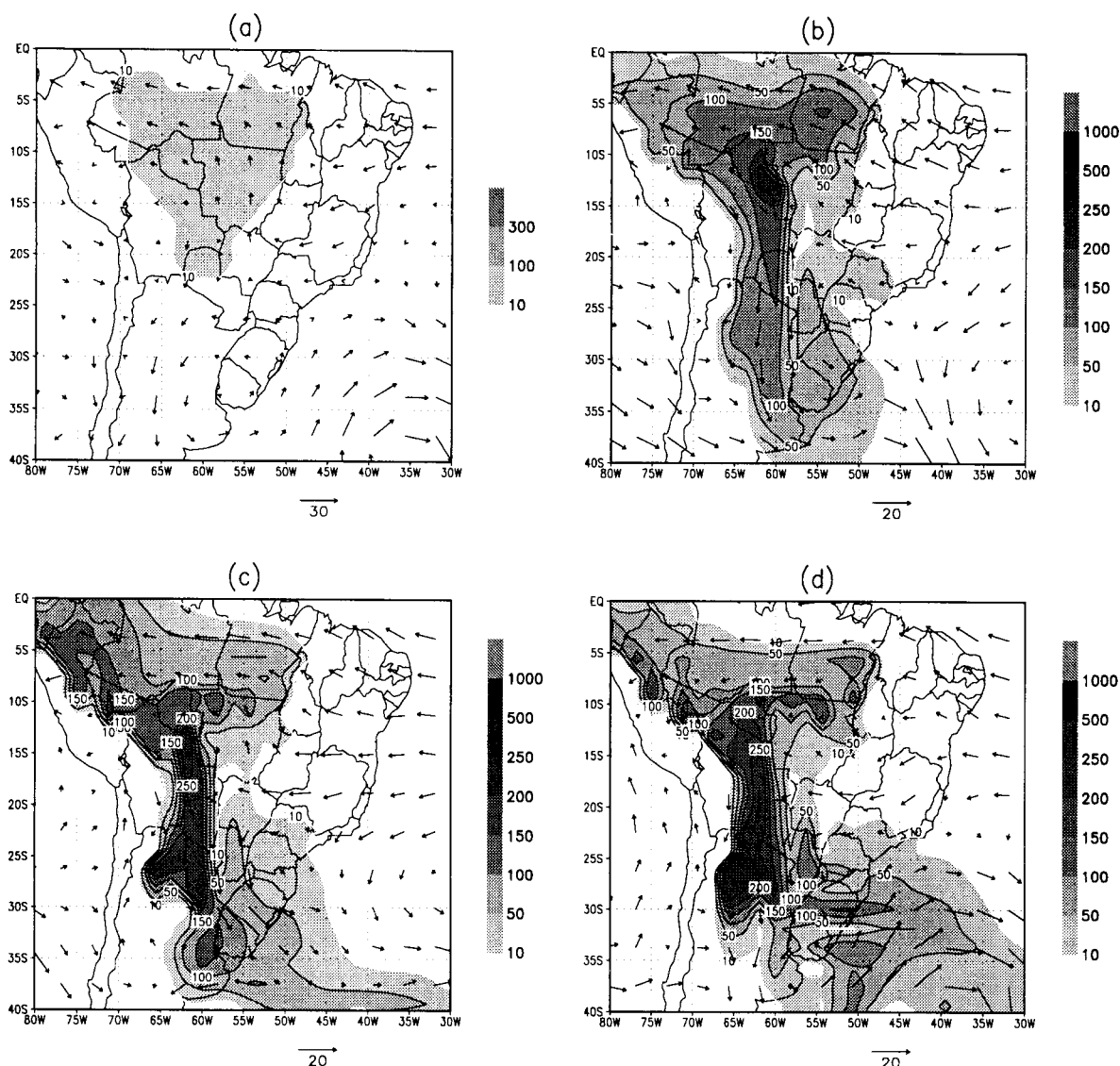
The first simulation of the aerosol spreading from four separate fire regions during the period from August 20 to 29, 1995, is demonstrated (Figures 2 and 3). The centers of the regions were placed at the points with coordinates (1) 56°W, 9.5°S (the region of Alta Floresta); (2) 52°W, 18.5°S (between Campo Grande and Brasília); (3) 55°W, 17°S (between Campo Grande and Cuiabá); and (4) 48.5°W, 13.5°S (between Porto Nacional and Brasília). The initial conditions for the smoke concentration were set quasi-uniformly with the average density in the atmospheric column about of 0.06 g m $^{-2}$  and the geographic configuration subjectively extracted from the GOES-8 visible image at 1145 UTC on August 20, 1995 (see Figures 1a and 2a). As shown in Figures 2a and 2b, from August 20 to 23, 1995, initially, the simulated aerosol moved westerly from the Alta Floresta region and southerly from northern Paraguay. By



**Figure 4.** Cumulative weekly number of fires in the model grid cells (a) for August 18-24, and (b) for August 25 - 31, 1995.

August 29 it reached 35°S. The locations of the different aerosol sources are better seen in Figure 2b. After August 23, 1995, the simulated aerosol began to spread southerly from the Cuiabá region and formed a narrow current which arrived at the latitude belt of 30°S-35°S (see Figure 2c).

The vertical structure of the southerly simulated aerosol currents can be seen in the vertical cross sections of the aerosol concentration along 25°S in Figure 3. Figure 3a shows a cross section of the simulated aerosol current which includes aerosol particles from the Rondonia region. In Figure 3b one can see the additional simulated



**Figure 5.** Simulated aerosol concentration ( $\mu\text{g m}^{-3}$ ) and wind ( $\text{m s}^{-1}$ ) at 850 hPa: (a) August 20, 1995 (initial condition); (b) August 23, 1995; (c) August 26, 1995; and (d) August 29, 1995, for the experiment with location of the aerosol sources in the burning areas.

aerosol current from the Cuiabá region. Figures 3c and 3d show the evolution of these simulated aerosol currents. On account of sedimentation, aerosol particles have the marked redistribution of heights depending on their lifetime in the atmosphere.

#### 4.2. Location of Aerosol Sources in Burning Areas

For determination of the burning areas during the SCAR-B period, data of the NOAA operational satellite monitoring of fires have been used. The fire monitoring data are produced by the National Institute for Space Research/INPE (Brazil) and include cumulative weekly number of fires in grid cells of  $0.5^\circ$  latitude by  $0.5^\circ$  longitude. The data were used for 2 weeks, August 18–24 and 25–31, 1995. The data have been remapped onto the model cells (see Figure 4). The fire numbers have

been used for the determination of aerosol sources in the model grid points

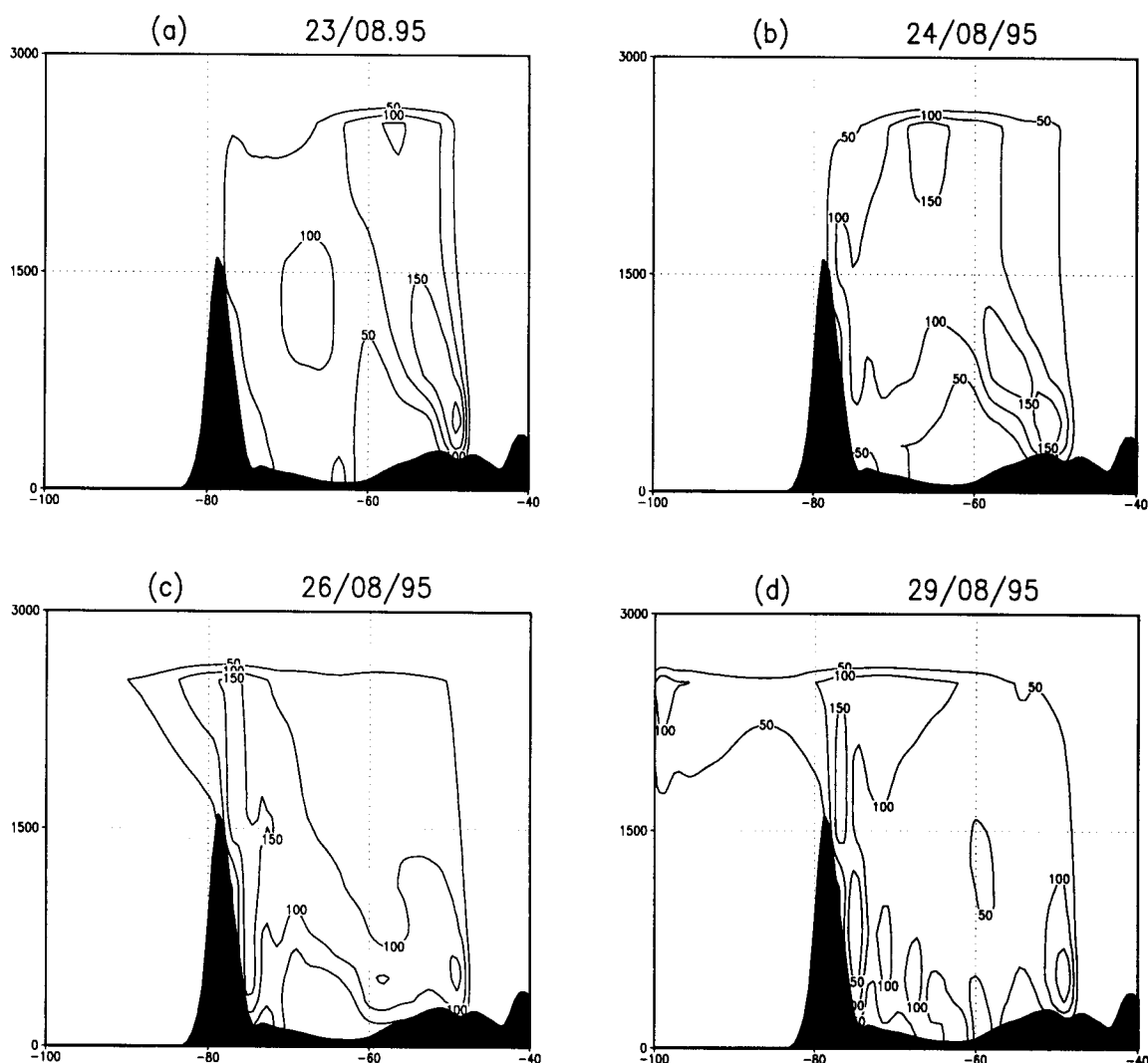
$$\frac{S}{\rho} = \frac{gS_0}{100\Delta P} w(\lambda, \varphi, t), \quad (15)$$

where  $S_0 = 2.25 \times 10^{-6} \text{ g m}^{-2} \text{ s}^{-1}$ ,  $\Delta P = 300 \text{ hPa}$ , and  $w(\lambda, \varphi, t)$  is the dimensionless weight function proportional to the number of fires in the model grid point  $k$ ,  $n_k$ ,

$$w_k = \frac{n_k}{\max_j(n_j)}. \quad (16)$$

The value of  $w$  lies in the limits:  $0.03 < w \leq 1$ .

Figure 5 shows the time evolution of the simulated aerosol concentration in  $\mu\text{g m}^{-3}$  on the pressure level 850 hPa. One can see that the principal features of the aerosol spreading are consistent with the aerosol spreading from the separate sources in the first experiment:



**Figure 6.** Simulated aerosol concentration cross section ( $\mu\text{g m}^{-3}$ ) along  $5^\circ\text{S}$ : (a) August 23, 1995; (b) August 24, 1995; (c) August 26, 1995; (d) August 29, 1995 for the experiment with location of the aerosol sources in the burning areas.

The main difference is that aerosol was also carried from the continent to the Pacific Ocean in the latitude belt from  $5^\circ\text{S}$  to  $5^\circ\text{N}$ . The vertical structure of this current is shown in Figure 6 for the vertical cross section of the simulated aerosol concentration in  $\mu\text{g m}^{-3}$  along  $5^\circ\text{S}$ . It should be noted that the values of the aerosol concentration are close to the observed values during the SCAR-B experiment [Artaxo *et al.*, 1996].

To estimate the aerosol amount for the second experiment, the components of the aerosol balance have been calculated. They are represented in Table 1. shows the time evolution of the simulated aerosol concentration. The total aerosol emission, 3.143 Tg, during 10 days, can be compared with annual aerosol emission in tropical America, 22.0 Tg [Penner *et al.*, 1991a].

#### 4.3. Estimation of Optical Depth

The quantity of the total aerosol mass in the atmospheric column  $m = \frac{1}{g} \int \chi \rho dp$  can be related to optical

depth  $\tau$  by

$$\tau = \gamma m, \quad (17)$$

where  $\gamma$  is a specific extinction coefficient. The optical depth values may be compared with observations. The value of  $\gamma = 2.73 \text{ m}^2 \text{ g}^{-1}$  has been derived for the spectral channel  $0.67 \mu\text{m}$  from measured physical characteristics (mass scattering and absorption efficiency, and single-

**Table 1.** Components of Aerosol Mass Balance for Experiment With Source Locations in Burning Areas

Component	1995	Value	Units
Initial aerosol mass	August 20	0.6930	Tg
Total Aerosol Emission	August 21-29	3.1433	Tg
Total Aerosol Flux Through Boundaries	August 21-29	-0.5679	Tg
Aerosol Mass	August 29	3.2684	Tg

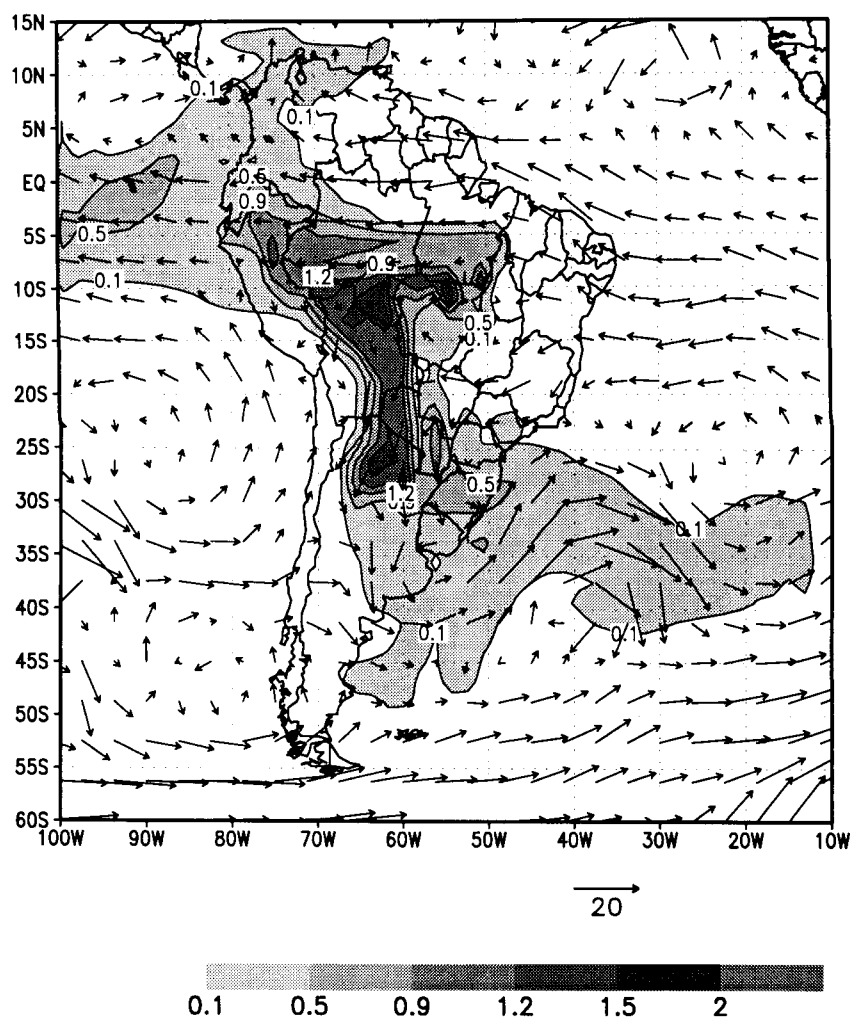


Figure 7. Optical depth of the aerosol on the surface on August 29, 1995, for the experiment with location of the aerosol sources in the burning areas.

scattering albedo) in regional hazes in Brazil during the SCAR-B experiment [Reid *et al.*, 1996]. Figure 7 shows the estimated optical depth of the aerosol for August 29, 1995. The calculated values are similar to the values of the observations for biomass burning periods [Kaufman *et al.*, 1992]. The calculated large-scale pattern of the aerosol distribution for August 29, 1995, shows a good

agreement with the observed haze on GOES-8 visible image (see Figure 1b). However, the agreement of the calculated and observed values of the optical depth for local points is not so good. Table 2 shows the (1) model estimated and (2) observed optical depth for the three stations. The observed data have been taken from the AERONET (Aerosol Robotic Network) data archive.

Table 2. Model Estimated and Observed Optical Depth Values for Stations From August 22 to 29, 1995

Station	August 1995							
	22	23	24	25	26	27	28	29
Alta Floresta								
a	1.30	0.95	0.83	0.95	1.11	1.20	1.20	1.32
b	1.18	1.88	1.13	1.11	1.12	1.26	1.30	1.34
Brasília								
a	0.04	0.04	0.04	0.02	0.02	0.02	0.03	0.02
b	0.08	—	0.08	0.08	0.07	0.06	0.08	0.09
Cuiabá								
a	0.06	0.13	0.16	0.09	0.09	0.11	0.12	0.16
b	0.11	0.04	0.12	0.06	0.17	0.08	—	0.37

The a is model estimated and b is observed optical depth values.



Although the optical depth level was simulated correctly for the stations, there is a discrepancy between estimated and observed small optical depths. It may be linked with the formation of aerosol density for Brasília and Cuiabá stations by local small-scale sources during August 22-29, 1995.

## 5. Conclusions

The transport model for the estimation of tracers from biomass burning areas has been developed on the basis of the semi-Lagrangian technique. The model includes principal processes which form large-scale tracer spreading for dry season: horizontal and vertical advection, sedimentation of aerosol particles, and horizontal turbulent exchange. No vertical diffusion is included in the model because poor boundary layer large-scale analysis data have been used for aerosol transport computation. They do not make it possible to estimate good parameters of the convective boundary layer. In fact, for burning areas the vertical turbulent exchange was added in the transport model by a source term equation (15) which includes full complex subgrid vertical transport from the surface to the atmosphere. The model has the property of tracer mass conservation that permits its use for balance calculations.

The simulation of the aerosol spreading for the SCAR-B period from August 20 to 29, 1995, showed that the air mass located below 2 km moved mainly to the south and carried the smoke until 30°S. A similar transport of the aerosol is observed on the GOES-8 satellite images. Another significant transport of aerosol was from the Alta Floresta region to the northwest.

Although the model seems to have realistically captured the geographical distribution of aerosol emanating from biomass burning areas during SCAR-B, it still needs improvement to represent the quantitative distribution of optical depth.

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