Estimating the Climate Impact of Biomass Burning Aerosols Using the NCAR-CCM3 in the Amazon

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Introduction

Aerosols are important for the climate system. They are known to scatter and absorb solar and infrared radiation, termed the direct effect, while providing a nuclei site for water vapor, termed the indirect effect, i.e., acting as a cloud condensation nucleus (CCN) altering the cloud's optical depth (Twomey 1977). Previous modeling studies of both effects have produced a possible range of values for the magnitude of the aerosol forcing, thereby warranting further investigation.

A range of values have surfaced from studies that quantify aerosol effects on climate. Boucher and Anderson (1995) found a ±20% uncertainty in estimating the direct effect of the sulfate aerosol when varying its size and chemical form. Lacis et al. (1992) approximated the global radiative forcing due to the direct effect of sulfates to be -1 W/m^2 with an uncertainty of 2, while Penner et al. (1994) determined a global-mean forcing of -0.6 W/m^2 with an uncertainty of 2.3 and Charlson et al. (1992) determined a value of -1.3 W/m^2. Jones et al. (1994) estimated a global average for the indirect effect at the top of the atmosphere due to sulfate aerosols to be -1.3 W/m^2 compared with the Charlson et al. (1992) value of -1 W/m^2. Penner et. al. (1994) evaluated global-mean direct radiative forcing for biomass burning aerosols to be -0.8 W/m^2 (with an uncertainty factor of 2.7) compared with earlier work (Penner et al. 1992) that found -1 W/m^2 for the direct and the indirect effect, respectively. By using more recent data coming from the SCAR-B project (August-September 1995), Hobbs et al. (1996, 1997) recalculated some of the parameters used by Penner and estimated a new value of -0.26 W/m^2, about a factor of 3 less than that of Penner. By working with satellite data over the Amazon Basin and Cerrado, Kaufman and Fraser (1997) recently reported that the smoke increased cloud reflectance from 0.35 to 0.45, while reducing droplet size from 14 µm to 9 µm. During the 3 months of biomass burning in the dry season, they found that the smoke-cloud forcing of climate in this region was only -2 W/m^2 much smaller than that inferred from the models.

Given the increase in the reliability of recent data about the smoke optical properties, it is time to design schemes to incorporate both the direct and indirect effect of smoke aerosols into climate models. The primary goal of this work is to estimate the global climate impact due to smoke aerosols from biomass burning using the National Center for Atmospheric Research (NCAR)-Community Climate Model, Version 3 (CCM3). Analysis of data from the AERONET project was used to define a more realistic average of the optical/radiative properties of smoke particles from biomass burning in the Amazon, and also, to provide relevant information about the cloud-aerosol interactions. This information was put into the context of a general circulation model (GCM), the NCAR-CCM3, and then the cloud/radiative scheme of the standard model was modified to include both the direct and indirect effect of the aerosols. Our research contributes to the use of aerosol climate modeling by providing a scheme in which the aerosol influences can be explicitly represented in a GCM.

Description of the Model

Understanding the Processes Through Data Analysis

A network of sunphotometers has been installed throughout the world (AERONET) to determine aerosol size distributions and concentrations, as well as their effects on solar radiation (Holben et al. 1996), through continuous monitoring of aerosol optical thickness and sky radiance. The data from the AERONET project was analyzed to characterize the properties of the smoke aerosols in the Amazon where biomass burning is significant.

Incorporation of the Direct Effect of the Smoke Aerosols into the Radiative Scheme of NCAR-CCM3

The radiative scheme of NCAR-CCM3 uses the δ-Eddington approximation dividing the solar spectrum into 18 intervals from 0.2 µm to 5.0 µm, with solar flux fractions specified for each interval. It also allows for seasonally and diurnally varying solar input; molecular, cloud, aerosol, and surface scattering; along with H_2O, O_3, CO_2, O_2, CH_4, N_2O, CFC11, CFC12, cloud, aerosol, and surface absorption. It computes reflection and transmission assuming homogeneously mixed layers, and adds the layers assuming scattering between layers to be isotropic. The direct solar beam is distinguished from scattered radiation (Briegleb 1992; Kiehl et al. 1996). To incorporate the radiative properties of smoke aerosols into CCM3, we must specify the following:

- aerosol spectral optical depth
- aerosol spectral single scattering albedo
- aerosol spectral asymmetry parameter.

The above was determined by

- obtaining monthly averages of the optical depth at a visible wavelength (670 nm) for different regions of the Amazon where biomass burning is important.
- using the above data into the model of smoke optical properties developed by Remer et al. (1997) to compute the volume size distribution of the smoke aerosols.
- using both the calculated volume size distributions and an assumed "best" complex refractive index for this type of aerosol with a Mie theory code to derive the radiative optical properties of the smoke aerosols, i.e., the spectral optical depth, single scattering albedo, and asymmetry coefficient.

The smoke aerosol is considered here as a well-mixed three-level homogeneous layer (the levels closest to the surface), as done for the background sulfate aerosol already simulated in the standard model.

A Simple Model of the Indirect Effect of the Biomass Burning Aerosols in a GCM

Recently, Kaufman and Fraser (1997) reported a summary of the analysis of the advanced very high resolution radiometer (AVHRR) satellite data for the change in the cloud droplet size and reflectance with a change in the smoke optical thickness. We incorporated these data into the radiative scheme of CCM3 to compute the change in the droplet effective radius given a change in optical thickness of the aerosol due to biomass burning. The change in optical thickness was obtained from the difference of the smoke aerosol as calculated in the above section, and the background sulfate aerosol already included in the model (CCM3). Only the change in the droplet effective radius is considered here as the principal contributor to the indirect effect of the aerosol. Hence, we neglect changes in the cloud liquid water path or in the total cloud cover due to the smoke.

Simulations and Results

First, we performed sensitivity analyses by testing differences due to the uncertainty of the smoke aerosol properties. Then, we carried out 2-year GCM simulations of four different cases as follows:

- the standard "control" case (with no smoke aerosol added)
- only the direct effect of the smoke included
- only the indirect effect of the smoke included
- both direct and indirect effects included.

These tests allowed us to discern the importance of each effect and estimate the climate impact by examining the differences resulting from the smoke, specifically on net radiative fluxes, surface temperature, evapotranspiration, etc.

Figures 1 and 2 show the results for the net downward solar flux at surface after a 2-year simulation for each case. The smoke was put into the model only during the Amazon dry season (from June to October) each year. In addition, Table 1 shows the results for other fields such as the latent heat flux at surface and the surface temperature.

Discussion

Preliminary analysis of the above results show that the direct effect is the predominant effect in the radiative fields. However, we can observe a significant reduction (~25%) of the surface latent heat flux in the indirect case (with respect to the control case). Changes in the surface temperature are negligible as expected.

Additionally, in Figure 2 we can observe a significant change in the difference fields of the smoke in the southeast part of the Amazon (the Cerrado region). In this region we can actually observe a "cooling" effect of the aerosol (with respect to the control case). The reason for the above is principal because the optical depth and the reflective properties of the smoke aerosols in this region are much greater compared to the rest of the Amazon. In fact, we can observe also a kind of "warming" effect in the east part of the Amazon.

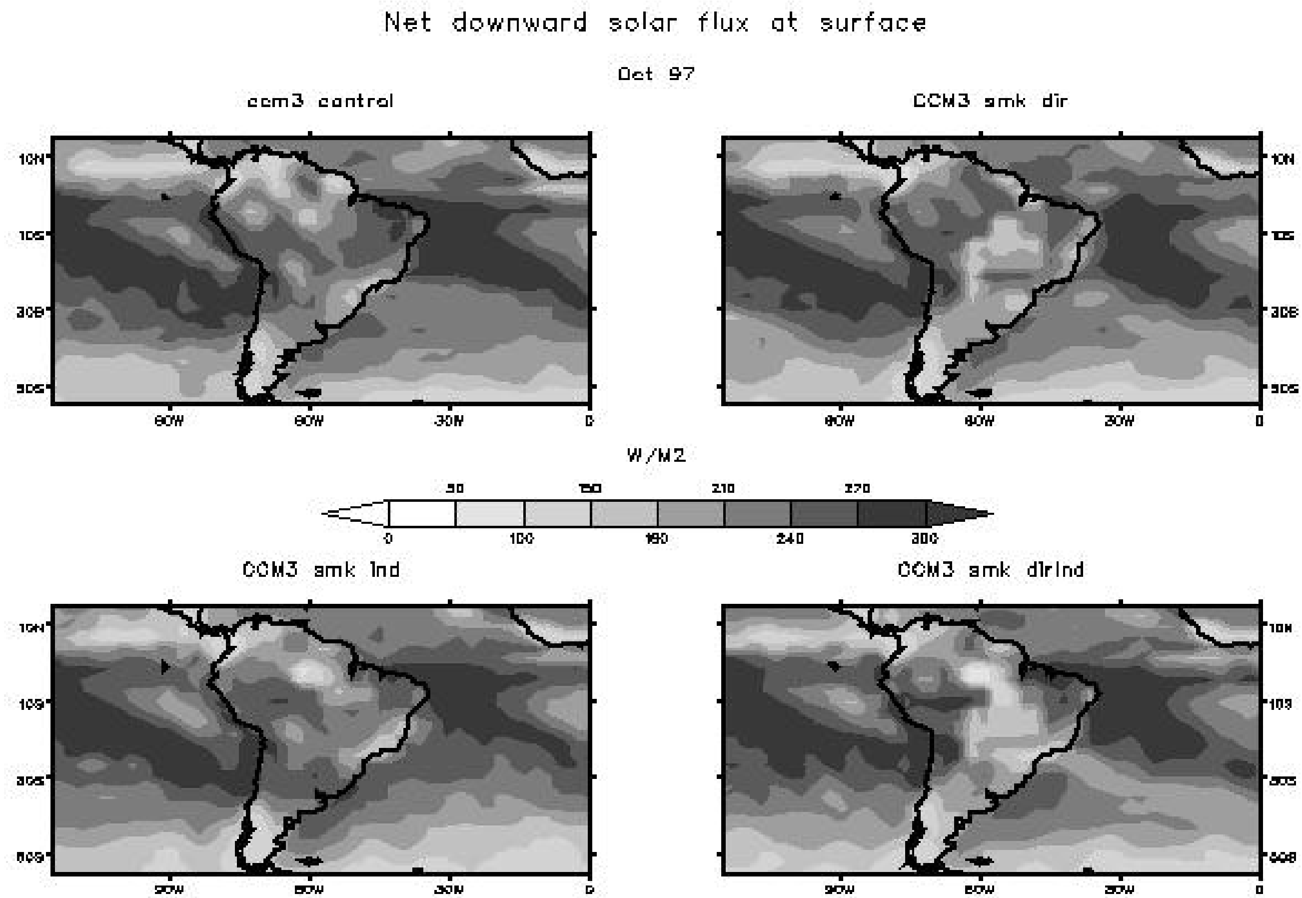

Figure 1. Results for October after a 2-year simulation of the net downward solar flux at surface for the control, direct, indirect and direct+indirect (dirind) cases in the Amazon region.

As mentioned above, these results are still preliminary and we are expecting to simulate at least 10 years for every case and compute more accurate statistics to determine whether or not these results are statistically significant and then give a better determination of the possible impact of the smoke aerosols in this part of the world.

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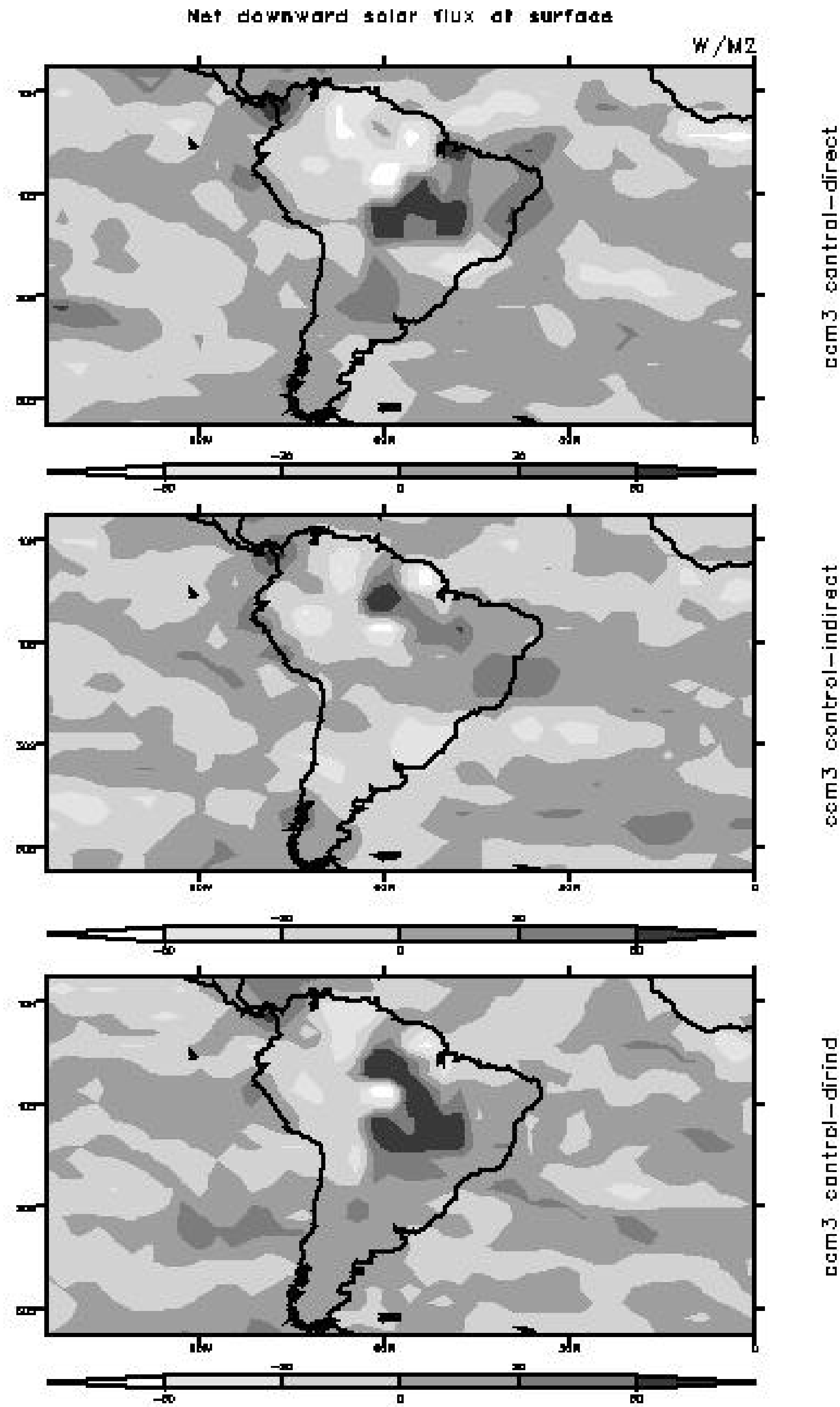

Figure 2. Difference fields for October of the net downward solar flux at surface. Control case minus (a) direct case, (b) indirect case, and (c) direct+indirect case.

Table 1. Amazon dry-season (June to October) averages.

Field	Control	2nd Direct	Year Indirect	Run Dirind	Con-Dir	Con-Ind	Con-Dirind
FSNS	214	201	208	200	-6.2%	-2.7%	-6.7%
FSNSC	242	229	242	229	-5.4%	0.1%	-5.3%
LHFLX	77	73	57	55	-5.0%	-25.4%	-28.9%
TS	298	298	298	299	-0.0%	0.2%	0.3%

FSNS Net downward solar flux at surface (W/m^2).
FSNSC Net clear sky downward solar flux at surface (W/m^2).
LHFLX Latent heat flux at surface (W/m^2).
TS Surface temperature (K).

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