Atmospheric Research 94 (2009) 409–421

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

A case study of the direct radiative effect of biomass burning aerosols on precipitation in the Eastern Amazon

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ARTICLE INFO

Article history:
Received 20 February 2008
Received in revised form 20 May 2009
Accepted 29 June 2009

Keywords:
Atmospheric modeling
Biomass burning
Precipitation
Aerosol

ABSTRACT

Numerical experiments with the Brazilian additions to the Regional Atmospheric Modeling System were performed with two nested grids (50 and 10 km horizontal resolution, respectively) with and without the effect of biomass burning for 8 different situations for 96 h integrations. Only the direct radiative effect of aerosols is considered. The results were analyzed in large areas encompassing the BR163 road (one of the main areas of deforestation in the Amazon), mainly where most of the burning takes place. The precipitation change due to the direct radiative impact of biomass burning is generally negative (i.e., there is a decrease of precipitation). However, there are a few cases with a positive impact. Two opposite forcing mechanisms were explored: (a) the thermodynamic forcing that is generally negative in the sense that the aerosol tends to stabilize the lower atmosphere and (b) the dynamic impact associated with the low level horizontal pressure gradients produced by the aerosol plumes. In order to understand the non-linear relationship between the two effects, experiments were performed with 4-fold emissions. In these cases, the dynamic effect overcomes the stabilization produced by the radiative forcing and precipitation increase is observed in comparison with the control experiment. This study suggests that, in general, the biomass burning radiative forcing decreases the precipitation. However, very large concentrations of aerosols may lead to an increase of precipitation due to the dynamical forcing associated with the horizontal pressure gradients.

1. Introduction

During the dry season biomass burning is certainly the major source of atmospheric aerosols in South America away from the megacities (Artaxo et al. 1990, 1994; Echalar et al., 1998). Modeling studies have indicated the potential impact of biomass burning on precipitation (Freitas et al., 2005). However, in spite of the evidence based on the physical reasoning associated with the direct radiative effect (through the thermodynamic stabilization of the lower troposphere) on the precipitation, not all model results agree on the sign of the impact, i.e., some results show a positive effect while others show negative effect on precipitation (Intergovernmental Panel on Climate Change — IPCC, 2001). The main objective of this paper is the analysis of a collection of short numerical simulation runs with a high resolution atmospheric model of the direct radiative impact of biomass burning on precipitation in a representative region in the Amazon Deforestation Arc. In this collection, some results indicate precipitation reduction and others an increase. A physical mechanism, based on the dynamical impact on the low level local circulation patterns associated with the aerosol plumes is explored in order to explain the precipitation increase.

Rudich et al. (2003) describe the relationship between convective cloud formation and oil fire plumes. The authors detected convective clouds above smoke plumes emerging from Kuwait oil fires in the year 1991 by analyzing images

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doi:10.1016/j.atmosres.2009.06.016

obtained from the Advanced Very High Resolution Radiometer (AVHRR). Some figures in Rudich et al. (2003) reveal that smaller convective clouds also were formed at the periphery of the smoke plumes, probably a similar mechanism to the one proposed here. That same mechanism is also explored in Klüser et al. (2008) where the authors concluded that absorption of solar radiation by aerosols not only can act to suppress cloud formation (e.g. Kaufman and Fraser, 1997; Ackerman et al., 2000; Koren et al., 2004), but also to induce convective clouds in suitable environments.

A few observational studies on the precipitation regime in China suggest that the aerosol emission by biomass burning may substantially affect the precipitation pattern in that region (Xu, 2001). According to the author, the diabatic heating associated with the aerosol emission displaces the West Pacific Subtropical High and the monsoon rain-belt to the south. According to Penner et al. (2001) this mechanism is caused by the change of circulation associated with the scattering effect and the absorption of solar radiation by the aerosols, altering the temperature and atmospheric pressure. Xu (2001) and Menon et al. (2002) also point out that the influence of aerosols on precipitation may be larger than the effect of increases in sea surface temperature in Southern China. However, Cheng et al. (2005) sustain that, due to the complexity of the effect of the aerosols in precipitation (thermodynamic effect and on the microphysical character of the clouds), its real effect may be covered up by the natural variability of the large-scale dynamical control.

Representative measurements of the various organic carbon species in aerosols and the differentiation between black and organic carbon still require improvement in order to fully understand the radiative impact of the aerosols. However, substantial progress has been made in recent years with regard to the emission factors, i.e., the amount of aerosol emitted per amount of biomass burned, based on controlled experiments (Procópio et al., 2004). Most of the biomass burning in the Southern Amazon and Central Brazil occurs during the dry season between July and October (Gan et al., 2004). During this period, biomass burning is intensified primarily due to deforestation (Echalar et al., 1998). During the peak of the burning season in Central South America the number of particles in the air goes up one order of magnitude from the values during the rest of the year (Martins et al., 1998). Solar radiation and in particular the Photosynthetically Active Radiation (PAR) reaching the surface is reduced by about 10–30% reducing surface temperature and light available for plant growth (Schafer et al., 2002). Particulate matter containing black carbon together with greenhouse gases absorbs radiation causing warming. The combination of a cooler surface (by a couple of degrees) due to lack of solar radiation and a warmer boundary layer due to absorption increases the thermal stability and reduces the chances of cloud formation, thus reducing the possibility of rainfall (Ramanathan et al., 2001). Freitas et al. (2005) indicated the possibility of rainfall decrease in the La Plata Basin (South America) as a response to the radiative effect of the aerosol load transported from biomass burning over the Cerrado and Amazon regions. From a purely observational point of view, Fu and Li (2004) have found some evidence that biomass burning aerosols might be influencing the rainfall distribution in the beginning of the wet season, based on comparisons between observed data and ECMWF precipitation estimates based on the reanalysis (effect of biomass burning aerosols is not included in the reanalysis).

Biomass burning also plays an important role in the hydrological cycle, due to modification of the precipitation and cloud albedo by the effect in the cloud microphysical processes associated with water condensation. The aerosols may act upon as cloud condensation nuclei (CCN) (Crutzen and Andreae, 1990; Roberts and Andreae, 2001; Roberts et al., 2003) and the increase of the aerosol concentration is associated with the increase of the concentration of CCN's, causing a decrease in the size of warm cloud droplets. This process diminishes the possibility of warm cloud precipitation, increasing the lifetime of the cloud (Andreae et al., 2004). This effect has been shown to be important in the Amazon basin (Khain et al., 2005), but is not explored in this paper and requires much further research.

2. Methodology

The numerical experiments were performed with the BRAMS-2.0 which is a version of the RAMS model (Cotton et al., 2003) that contains a few additional functionalities in order to represent some features associated with the tropical region (http://brams.cptec.inpe.br/). An emission model for the gases and particles and a more complex radiative transfer module to solve the processes associated with the aerosols (CARMA – Toon et al., 1988) were included in the model as an additional radiation parameterization option to BRAMS (Freitas et al., 2005; Vendrasco, 2006). In the present study only the direct radiative effect is treated, by considering the particulate matter as particles having a black carbon core density of 1.85 $g\,cm^{-3}$ and an organic shell density of 1.31 $g\,m^{-3}$, forming a stratified sphere, following the formulation of Toon and Ackerman (1981). Studies by Reid et al. (1998) show that the average density of the smoke particles over the Amazon Region is about 1.35 $g\,cm^{-3}$. After emissions, the model considers the aerosol as a scalar, i.e., non reactive, and it is transported and diffused by the BRAMS advection and diffusion equations. Dry deposition is indirectly simulated by considering an aerosol lifetime of 3 days.

It is important to point out that the aerosol role is not fully treated in the model. Some relevant processes, such as those associated with cloud microphysics and wet deposition are not considered. The presence of aerosol in the atmosphere can alter the cloud droplet number, which is a function of the updraft velocity. Thus, the cloud radiation properties can be changed throughout the interaction with aerosols. Scavenging by precipitation, not included in the model formulation, is a relevant removal process as the particle size increases. Another important feature which is not considered in the model is the fact that growth of particles modifies its life time in the atmosphere. Therefore, in the real atmosphere, it is possible that long distance transport of particles no longer exist, being aerosol effect concentrated close to its source. Finally, absorption and scattering rates can be altered by particle growth. However, in spite of such limitations, the model used here is suitable for this work in the sense that the main goal is the investigation of the aerosol direct radiative effect on precipitation.