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# Emissions of gases and particles from biomass burning during the 20th century using satellite data and an historical reconstruction

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A new dataset of emissions of trace gases and particles resulting from biomass burning has been developed for the historical and the recent period (1900–2005). The purpose of this work is to provide a consistent gridded emissions dataset of atmospheric chemical species from 1900 to 2005 for chemistry-climate simulations. The inventory is built in two steps. First, fire emissions are estimated for the recent period (1997–2005) using satellite products (GBA2000 burnt areas and ATSR fire hotspots); the temporal and spatial distribution of the $CO_2$ emissions for the 1997–2005 period is estimated through a calibration of ATSR fire hotspots. The historical inventory, covering the 1900–2000 period on a decadal basis, is derived from the historical reconstruction of burned areas from Mouillot and Field (2005). The historical emissions estimates are forced, for each main ecosystem, to agree with the recent inventory estimates, ensuring consistency between past and recent emissions.

The methodology used for estimating the fire emissions is discussed, together with the time evolution of biomass burning emissions during the 20th century, first at the global scale and then for specific regions. The results are compared with the distributions provided by other inventories and results of inverse modeling studies.



## 1. Introduction

During the 20th century, human activities and biomass burning have produced substantial emissions of trace gases and particles into the atmosphere. These emissions have resulted in significant perturbations in the radiative balance of the atmosphere and in air quality at regional and global scales. The definition of emission regulation policies and the evaluation of the effects of these policies require an accurate estimate of atmospheric emissions and of their temporal evolution.

Since the late seventies, biomass burning has been known to be a major source of aerosols and gases in the atmosphere (Seiler and Crutzen, 1980; Andreae et al., 1988). Globally, biomass burning contributes today to about 50% of the total direct CO emissions (Pétron et al., 2004) and about 15% of surface $NO_x$ emissions (IPCC, 2001). Pollutants emitted as a result of biomass burning can be injected into the atmosphere at relatively high altitudes, and be rapidly transported in the free troposphere. For example, it has been shown that polluted air masses resulting from fires in Brazil can be transported over the tropical Atlantic towards Africa and the Indian Ocean (Singh et al., 1996); plumes originating from Alaskan fires in 2004 have also been detected in Europe, leading to an increase in the ozone background concentration, and even to high ozone episodes (Real et al., 2007).

Wildfires are known to have a large interannual variability (Duncan et al., 2003), and the resulting emissions are therefore very variable in time and space. Satellite sensors such as the Along-Track Scanning Radiometer (ATSR, Arino and Plummer, 2001) and Moderate Resolution Imaging Spectroradiometer

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(MODIS, Justice et al., 2002), provide routinely the location of fires observed under the satellite overpass at a spatial resolution of 1 km; the quasi-global coverage from these observations has allowed a better identification of fires interannual variability at the global scale over the past few years (Duncan et al., 2003; van der Werf et al., 2006). These studies have shown that biomass burning accounts for most of the interannual variability of the emissions of several chemical compounds. In the tropics, this variability is in part linked to the El Niño-Southern Oscillation (ENSO), which produces episodes of droughts in equatorial and tropical regions, and therefore increases fire activity in these regions. During the 1997–1998 EL Niño episode, intense fires were observed in Indonesia, more particularly in peatland areas, leading to strong emissions of chemical species (van der Werf et al., 2006). In boreal regions, a very high interannual variability is observed as well, which has been proven to be correlated with the Arctic Oscillation and associated temperature anomalies (Baltzer et al., 2005). These large changes in the spatial and temporal distribution of emissions have to be taken into account when simulating the evolution of the atmospheric composition, and its impact on climate. A quantitative description of this variability has been made possible by the analysis of satellite data, but the satellite record is limited to the recent years (Liousse et al., 2004).

The evolution of fire emissions during the last century is not well established and only a few studies have evaluated these emissions over several decades (Mouillot and Field, 2005; Mouillot et al., 2006; Schultz et al., 2008a); the quantification of the evolution of historical emissions is however essential for understanding the distribution of tropospheric species during the past century, and for the understanding of chemistry-climate interactions.

The purpose of the work described here is to provide a consistent gridded emissions dataset of atmospheric chemical species from 1900 to 2005 for long-term chemistry-climate simulations. This dataset covers the period 1900–2000 on a decadal basis, as well as the recent period (1997–2005) on a annual basis. The historical and the recent emission inventories are built with different methods and types of data: for the recent period, observations from space-borne instruments are used, while for the historical period we have used an historical reconstruction of burnt areas from Mouillot and Field (2005). The recent period 1997–2005 is used as the reference point for the 1990s decade, which is also provided in the historical inventory: the biomass burning emissions estimate provided for the 1990s decade from the historical reconstruction is scaled, for each ecosystem, so that it matches the average 1997–2005 estimate, ensuring consistency between past and recent emissions.

For the recent period, different types of products have been derived from space-borne instruments for the observation of fires. Distributions of fire counts obtained from instruments such as ATSR (since 1995) or MODIS (since November 2000) provide the location of fires but are not sufficient for estimating the real area and amount of biomass which burned, and consequently the emissions. Satellite imagery products providing directly the burnt areas are just becoming available for longer time periods, and are currently under evaluation (Brivio et al., 2009). In this study, the GBA2000 (Grégoire et al., 2003) satellite product providing burnt areas for the year 2000 is used, together with ATSR fire hotspots time series over the 1997–2005 period. Similar methods, where different satellite products are combined, have been described by van der Werf et al. (2006) and Giglio et al. (2006).

This inventory is referred to as GICC (Global Inventory for Chemistry-Climate studies). After a description of the methodology used, the emission estimates obtained for the entire period are discussed and compared with other available inventories. Although the inventory provides the emissions of a long list of species (greenhouse gases, ozone precursors, particles and their precursors), the paper focuses mainly on the emissions of carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxides ($NO_x$) and black carbon (BC).

## 2. Methodology: estimation of biomass burning emissions for the 1997–2005 period

The emission of a species X resulting from fires, E(X), is expressed (Seiler and Crutzen, 1980) as the product, for each vegetation class i, of the burnt area $BA_i$ (in $m^2$), the biomass density $BD_i$ (in kg $m^{-2}$), the burning efficiency $BE_i$ and the emission factor of species X, $EF_i(X)$:

$$E(X) = \sum_{i=1}^{N} BA_i \cdot BD_i \cdot BE_i \cdot EF_i(X) \quad (1)$$

where $N$ is the number of vegetation classes taken into account.

The biomass density (BD) or fuel load provides the available biomass per surface unit; the burning efficiency (BE) corresponds to the percentage of the biomass which effectively burns. The emission factor gives the amount of chemical species emitted for a given amount of biomass burned. In this section, the quantification of each component of equation (1) is discussed.

### *2.1. Satellite fire observations and land cover map*

In this study, burned areas over the past decade are obtained or derived from the following space-borne observations:

- The GBA2000 (Tansey et al., 2004) product provides global burnt areas for the year 2000 on a monthly basis. It is derived from visible and infrared measurements from the SPOT4/VEGETATION space-borne instrument, launched in March 1998. An analysis of the images provides a cartography of the burnt areas at a 1 km resolution.
- The ATSR WFA (World Fire Atlas; Piccolini and Arino, 2000) product provides daily maps of fire hotspots at a 1 km resolution since 1995. It is derived from the ATSR radiometer (Arino and Plummer, 2001) on-board ERS-2 (1995–2003) and ENVISAT (since 2003), which measures the radiation originating at the earth surface in the visible, mid-infrared and thermal infrared. The algorithm applied to detect fire spots is identical throughout the 1997–2005 period considered in this study, and provides therefore a consistent dataset for the full period under consideration. Only nighttime fires are provided, which means that not all fire events are detected, compared to the total fire activity. Other hotspots such as volcanoes or gas flares can be removed since these are observed continuously (Mota et al., 2006). In this study we used the dataset from Mota et al. (2006), regridded at a 0.5° resolution.

The global land cover distribution is needed to determine the type of vegetation which is burning, when a fire is detected. In this study we used the GLC2000 map (Bartholomé and Belward, 2005), derived from the SPOT/VEGETATION space-borne system, at a 1 km resolution. The biomass densities (BD), burning efficiencies (BE), and emission factors (EF) of GLC2000 vegetation types were derived from values published in Michel et al. (2005) for the UMD land cover map (Defries et al., 1998; Hansen et al., 2000). Correspondences between the UMD and GLC2000 vegetation cover classes have been established (Liousse et al., 2005, P. Mayaux, pers. com.); the related BD, BE and $CO_2$ emission factors are indicated in Table 1.