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Global wildland fire emissions from 1960 to 2000

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[1] In many regions of the world, fires are an important and highly variable source of air pollutant emissions, and they thus constitute a significant if not dominant factor controlling the interannual variability of the atmospheric composition. This paper describes the 41-year inventory of vegetation fire emissions constructed for the Reanalysis of the Tropospheric chemical composition over the past 40 years project (RETRO), a global modeling study to investigate the trends and variability of tropospheric ozone and other air pollutants over the past decades. It is the first attempt to construct a global emissions data set with monthly time resolution over such a long period. The inventory is based on a literature review, on estimates from different satellite products, and on a numerical model with a semiphysical approach to simulate fire occurrence and fire spread. Burned areas, carbon consumption, and total carbon release are estimated for 13 continental-scale regions, including explicit treatment of some major burning events such as Indonesia in 1997 and 1998. Global carbon emissions from this inventory range from 1410 to 3140 Tg C/a with the minimum and maximum occurring in 1974 and 1992, respectively (mean of 2078 Tg C/a). Emissions of other species are also reported (mean CO of 330 Tg/a, NO_x of 4.6 Tg N/a, CH_2O of 3.9 Tg/a, CH_4 of 15.4 Tg/a, BC of 2.2 Tg/a, OC of 17.6 Tg/a, SO_2 of 2.2 Tg/a). The uncertainties of these estimates remain high even for later years where satellite data products are available. Future versions of this inventory may benefit from ongoing analysis of burned areas from satellite data going back to 1982.

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1. Introduction

[2] The atmospheric abundance of trace gases and aerosols is largely determined by surface emissions of anthropogenic and natural origin. Anthropogenic emissions of greenhouse gases and air pollutants have risen dramatically over the past century and exert a noticeable influence on the Earth's climate and the welfare of its population [*Intergovernmental Panel on Climate Change*, 2001]. One important source of air pollutant emissions, particularly in tropical latitudes, are fires in the open vegetation (wildland fires). Although these fires are today mostly ignited by humans (either on purpose or inadvertently), the fire size and the amount of material burned depends on natural climatic and orographic factors and can vary drastically between individual years. Fire emissions in the boreal and midlatitude zones are dominated by individual large-scale burning events, while tropical fires often consist of many small-scale burns. Some recent studies have begun to assess the interannual variability of wildland fire emissions on the global or continental scale [cf. *Barbosa et al.*, 1999; *Wotawa et al.*, 2001; *Schultz*, 2002; *Generoso et al.*, 2003; *Duncan et al.*, 2003; *Soja et al.*, 2004; *van der Werf et al.*, 2004, 2006]. Their methodologies and results are rather different. Until the reasons for the discrepancies between these studies are clear, it must be noted that large uncertainties remain with respect to the annual amount of wildland fire emissions, regional and temporal variability patterns, and the longer-term trends. The present study can help to elucidate some of the differences

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between recent emission estimates. We analyzed much of the available literature and intercompared the results from different studies (see in particular the regional discussions in the auxiliary material).

[3] There are three main factors of uncertainty, which limit the potential accuracy of any global long-term biomass burning emission data set [*Ito and Penner*, 2005a]:

[4] 1. For burned areas, accurate long-term monitoring of fire scars has been performed only in few regions. Satellite retrievals of active fires and burned areas, which in principle allow for the monitoring of fires on the global scale, have only become available recently and are generally obtained only for the time period after 1995. These satellite fire products have yielded a lot of insight into the spatial and temporal patterns of fire occurrence. However, their quantitative use is still limited because of sensor limitations, orbital drift, cloud and smoke obscurence (together with poor sampling statistics), and retrieval problems which may vary for different ecosystems and observing conditions [*Kasischke et al.*, 2003; *Pereira*, 2003; *Boschetti et al.*, 2004; *Giglio and Kendall*, 2004]. Aerial surveillance of fires has been conducted mostly in the midlatitude regions of the Northern Hemisphere and such data may easily be biased due to incomplete and varying coverage of the region. While for some densely populated regions (e.g., Europe) fires were recorded rather comprehensively for long time periods, such data are difficult to obtain, because they were recorded by forest services on the provincial or regional level and are often not digitized.

[5] 2. For fuel consumption, fire severity, and therefore the amount of fuel that is actually combusted in a fire, depends on the fuel load and density, fuel moisture, vegetation type and phenological status, the organic content and moisture of the soil, and the rate of spreading (determined largely by wind speed, fuel consumption by fire, fuel bulk density, and topography). Many of these parameters are highly variable even within one fire and they are poorly determined on larger scales. Other factors which can influence fire susceptibility are herbivory by insects [*Williams and Liebhold*, 1995] and mammals [*Scholes and Archer*, 1997], as well as human intervention (forest management, deforestation, cultivation, and reforestation) [*Osborne*, 2000]. Few studies have attempted to take these factors into account explicitly, and there are very little data to support general parameterizations for global-scale modeling of fire emissions.

[6] 3. For emission factors, the amounts of individual chemically active trace species and aerosols released from a fire depend on the fuel type and fire characteristics and are often poorly determined [cf. *Andreae and Merlet*, 2001; *Liousse et al.*, 2004]. Generally, a more complete combustion (e.g., during the flaming stage of a fire) will lead to a larger fraction of highly oxidized species (e.g., CO_2, NO_x), while smoldering burns release more material in reduced form (e.g., CO, NH_3, and NMVOC species). Emission factors may vary with season [cf. *Ward et al.*, 1992, 1996; *Hély et al.*, 2003], and the fire characteristics can be very different even for fires occurring in neighboring regions at the same time (for example crown fires versus ground fires in the boreal zone).

[7] As a consequence of the poor data situation and the large variability between fires, any attempt to construct a spatially and temporally resolved global long-term inventory of wildland fire emissions will necessarily remain both crude and incomplete. The main purpose of the inventory presented here is its use as input data for global chemistry transport models, which simulate the atmospheric chemical composition over long time scales in the Reanalysis of the Tropospheric chemical composition over the past 40 years (RETRO) project (http://retro.enes.org). The main objective of this project is to investigate the causes for the observed trends and variability in pollutant background concentrations.

[8] The RETRO wildland fire inventory is the first attempt to explicitly prescribe global fire emissions and their interannual variability over such a long time period. *Duncan et al.* [2003] published a global inventory with annual variations from 1979–2000. In their study, the variability of emissions in some regions was estimated based on Total Ozone Monitoring Spectrometer (TOMS) aerosol index (AI) data. However, their method consists of the derivation of scale factors for an underlying climatological reference inventory [*Lobert et al.*, 1999] with its own uncertainties. Also, the TOMS AI data do not cover all fire regions and the relationship between AI and fire emissions is not entirely clear [*Ichoku and Kaufman*, 2005]. Furthermore, the scaling approach cannot be extended backward in time due to the lack of earlier satellite observations. Therefore, *Ito and Penner* [2005b] and *Mouillot and Field* [2005] used sparse reported information and some assumptions on variability patterns in order to estimate emissions prior to 1979. In contrast to these studies, the RETRO fire emission inventory is based on a bottom-up composite approach, which combines country level reports with recent satellite fire observations and a numerical model of fire spread and occurrence.

[9] The inventory presented in this study aims at reproducing the broad characteristics of wildland fires in different continental-scale regions and their variability and trend patterns. In the system of the RETRO emission inventories, the burning of biofuel for industrial or residential purposes and the burning of agricultural residues is treated as part of the anthropogenic activities. These emissions are included in a different data set and are described by *Pulles et al.* [2007] and *Schultz et al.* [2007] (available at http://retro.enes.org/publications/).

[10] This paper briefly describes the construction of the RETRO fire emissions inventory and reports the resulting emission estimates for a number of chemically active trace compounds including a discussion on the regional trends and variabilities. A detailed discussion of the tools and the input parameters for each region can be found in the auxiliary material together with a critical evaluation of previous studies.[1] The concluding section of this paper summarizes the remaining uncertainties and provides some suggestions for further work. The complete emission data sets are made available through the Web sites of the Global Emissions Inventory Activity (GEIA, http://www.geiacenter.org) and of the RETRO project (http://retro.enes.org/data_emissions/).

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GB003031.

Table 1. Region Definitions and Summary of Methodologies Applied for the Construction of the RETRO Vegetation Fire Inventory[a]

Region	Geographic Extent	Methodology for Estimating Average Area Burned[b]	Interannual Variability[c]	Seasonal Variability[d]	Geographical Distribution[e]
Alaska	50–70°N, 170–142°W	2	1	4	2
Canada	48–70°N, 142–60°W	1	1	1	1
Siberia + Mongolia[f]	45–78°N, 20–180°E	2, 4	1	2, 4	2
Contiguous United States	30–48°N, 135–85°W	2	1	2	2
Europe	country level[g]	2[g]	1[h]	4	2
Central America	0–28°N, 120–45°W	4	3, 4	2	3
South America	32–0°S, 70–30°W	4	3, 4	2	3
NH Africa	0–18°N, 17°W–40°E	4	3, 4	2	2, 3
SH Africa	38–4°S, 5–50°E	4	3[i], 4	2	3
India	3–28°N, 65–90°E	5	4	2	2
Continental SE Asia	8–35°N, 90–135°E	2, 5	2	2	2
Indonesia	20°S–8°N, 90–141°E	3	2, 3	3	4
Australia	42–13°S, 105–155°E	4	4	2	2

[a]For details, see the auxiliary material.
[b]Methodologies are 1, detailed fire statistics with explicit spatial and temporal resolution; 2, long-term annual fire statistics on country or province level; 3, combined statistical and satellite information for the late 1990s; 4, literature value from detailed regional studies; and 5, other.
[c]Methodologies are 1, explicitly reported burned areas for most of the period 1960–2000; 2, correlation with climate signal (ENSO); 3, interpolation of reported trends; and 4, model result.
[d]Methodologies are 1, explicit listing of individual fires; 2, screened GBA-2000 data (GWEM 1.4); 3, screened ATSR data; and 4, qualitative description based on literature.
[e]Methodologies are 1, explicit listing of individual fires; 2, random distribution of individual large fires; 3, GBA-2000 with statistical noise; and 4, ATSR data for different ENSO classes.
[f]Because of lack of specific information on Mongolia, data for Mongolia were assumed to be correlated with Siberia.
[g]Subregions defined for 18 country groups: Scandinavia, United Kingdom and Ireland, Germany, Poland, former Czechoslovakia, BENELUX, France, Spain, Portugal, Italy, Greece, Albania, Cyprus, former Yugoslavia, Hungary, Bulgaria and Romania, Austria and Switzerland, and Turkey.
[h]Explicit country level statistics are available only after 1989. Before this date, an average value with random variability is used.
[i]Tropical forests in Africa are included in NH statistics.

[11] While the main purpose of this paper is the documentation of a new emissions data set for global chemistry transport modeling, the material presented here may also provide some new insight into the reasons for disagreement between previous estimates of vegetation fire emissions. We hope that the results from this work can therefore be used as a reference for future studies on the impact of fires on the atmospheric chemical composition and that it can contribute to the understanding of the interannual variability of trace gas and aerosol measurements.

2. Methodology

[12] Because of severe regional inconsistencies between different recent inventories that are based on satellite data observations [*Hoelzemann*, 2006] it was concluded that a long-term global inventory is best constructed in a composite approach, using the most detailed information available for different regions. We define thirteen regions, which are typically of the size of a continent or subcontinent. As discussed by *Robinson* [1989], the spatial disaggregation of the inventory should reduce the overall uncertainty, but nevertheless uncertainties remain high for several regions and thus also globally. The methodology for prescribing the burned areas, the interannual and seasonal variability, and the geographical distribution of fires depends on the available input data and the broad-scale characteristics of fire in each region. The geographical boundaries of our regions and a summary of the selected approaches for estimating these parameters can be found in Table 1. Details on the choice of each parameter are provided in the auxiliary material.

2.1. General Approach

[13] The classical fire emissions equation is

$$E_i = A \times \mathrm{FL} \times \mathrm{BE} \times \mathrm{EF}(i). \quad (1)$$

Here E_i is the emission flux of species i, A is the burned area, FL denotes the fuel load, BE the burning efficiency, and EF(i) the specific emission factor [*Seiler and Crutzen*, 1980]. Many of the parameters required in this equation are very uncertain and highly correlated. This will exacerbate uncertainties and can easily introduce a bias if equation (1) is applied on larger regions. In order to avoid this problem and to allow for a broader intercomparison with other inventories, we simplify equation (1) and consider only two parameters for estimating the regional annual carbon release from fires E_C:

$$E_C(i,k) = A(i,k)E_{net}(i,k) \quad (2)$$

A is the burned area in region i and ecosystem class k, and E_{net} is the average amount of carbon per unit area directly emitted from fires. E_{net} is lower than the total carbon release, which would include emissions from decaying vegetation in the postfire phase. In our inventory, E_{net} is only dependent on the geographical region and ecosystem type and does not vary with time. As a consequence, the interannual variability is driven only by variations in the burned area A. We concede that variations in fuel load may be another important driver for the interannual variability of emissions, particularly in tropical savanna regions. However, larger fuel loads will often also lead to larger burned areas (on a regional scale), and we should therefore at least qualitatively reproduce the variability of emissions, provided that our burned area estimates are correct. We analyzed the relationship between burned area and carbon emissions from the recent Global Fire Emissions Database (GFED) version 2 [*van der Werf et al.*, 2006] and found that the correlation between these two parameters is generally better than 0.8 for the continental-scale regions considered in this paper, while the correlation between fuel load and carbon emissions is weaker [see also *van der Werf et al.*, 2006, Figure 4]. Weak correlation between area burned and carbon emissions is found for South America, for the combined region of Southeast Asia and Indonesia, and for Australia.

[14] In a second processing step, the regional annual carbon emissions are distributed in space and time in order to generate monthly gridded fields (see sections 2.6 and 2.7). Finally, we use these gridded monthly fields to derive the emissions of 27 trace gas and aerosol compounds based on constant ecosystem-dependent emission ratios as follows:

$$E_i = E_C \frac{\mathrm{EF}(i)}{\mathrm{EF}_C(\mathrm{CO_2}) + \mathrm{EF}_C(\mathrm{CO})} \qquad (3)$$

The fraction on the right-hand side of equation (1) approximates the emission ratio of species i to the total direct carbon emissions. $\mathrm{EF}_C(\mathrm{CO_2})$ and $\mathrm{EF}_C(\mathrm{CO})$ are the emission factors (in g C/kg dry matter (DM)) for CO_2 and CO, respectively.

2.2. Reg-FIRM and GWEM

[15] In the construction of the RETRO fire emissions inventory we made use of two different modeling tools, which we shall briefly describe here. More details can be found in the auxiliary material and in the cited literature.

[16] The Regional fire model (Reg-FIRM) [*Venevsky et al.*, 2002] is an extension of the Lund-Postdam-Jena (LPJ) global dynamic vegetation model [*Sitch et al.*, 2003], which simulates general fire dynamics in coarse resolution grid cells based on semiphysical models of fire spread. Reg-FIRM computes monthly mean estimates of fire ignitions and burned area based on climate data from the Climate Research Unit (CRU), population density maps from HYDE 3.0 [*Goldewijk*, 2005], and soil moisture and fuel amounts in the different LPJ carbon pools. In this work, we use Reg-FIRM to provide estimates of the burned area variability in areas where no detailed information is available (see Table 1 and the auxiliary material).

[17] The Global Wildland fire Emission Model (GWEM version 1.4 [*Hoelzemann et al.*, 2004; *Hoelzemann*, 2006]) calculates global, monthly fire emissions for several trace gases and aerosol species based on a combination of satellite fire data, statistical data, and the results from LPJ. Version 1.4 of GWEM contains several improvements compared to version 1.2, which is described by *Hoelzemann et al.* [2004]. Specifically, this version makes use of the following input data: monthly burned area estimates from GBA2000, fuel load in 5 carbon pools for each of 9 plant functional types from the LPJ model, and emission factors from *Andreae and Merlet* [2001] (with updates according to M. Andreae (personal communication, 2005)). The burning efficiency in each ecosystem is taken from *Reid et al.* [2005] and the geographical distribution of ecosystems is from *Friedl et al.* [2002]. Here, we do not make use of the emission estimates generated with GWEM, but only use its description of geographical and temporal fire patterns. Basically this is the fire distribution from the Global Burned Area (GBA) 2000 product [*Tansey et al.*, 2004], but with some filtering of agricultural land and a disaggregation into the major ecosystem classes described below.

2.3. Definition of Ecosystem Classes

[18] We define average burning properties (effectively $E_{net}(C)$) for four highly aggregated ecosystem classes in each of our 13 regions. The four classes are derived from a gridded land cover data set with 0.5° resolution in latitude and longitude, specifying the fractional cover of the 16 classes defined in the MODIS IGBP product [*Friedl et al.*, 2002]. Fires can occur in the three aggregate classes ‘‘forest’’ (consisting of all five IGBP forest classes and closed shrublands), ‘‘wooded’’ (open shrublands and wooded savanna), and ‘‘grass’’ (savanna and grasslands). The remaining classes (water, permanent wetlands, cultivated pastures, urban, snow and ice, and barren soils) were combined into a ‘‘nonburning’’ category. The ‘‘cropland/natural vegetation mozaic’’ class has been split equally between the ‘‘grass’’ and nonburning classes. Changes in the cropland distribution over the past 40 years were not taken into account as it was difficult to reconcile the land-use change data set of *Ramankutty and Foley* [1999] with the MODIS IGBP land cover data set. We realize that this may deemphasize some trends in fire emissions, particularly for the African, South American and South Asian continents, where land-use change has been most relevant over the past 40 years.

2.4. Burned Area

[19] There is a qualitative difference between fire in the boreal and midlatitude zones and tropical forest and savanna burning, and this difference is also reflected in the choice of methods applied in the construction of the RETRO inventory and especially in the selection of input data for burned area estimates (Table 1). In the boreal and midlatitude zones we tried to include explicit information on individual large fires or at least annual observed burned area estimates where available. This information was mostly obtained from the forest services on the national or province level. We cross-checked these official estimates of burned area with literature values for specific years, which were derived from different satellite products. Large differences (factor of 5) were found for the estimates from Russia. Therefore we applied a scaling factor to the burned area estimates from this region. For Canada, Alaska, the contiguous United States, and for Siberia, the official fire statistics date back into the 1960s. In spite of concerns about the robustness of these data for early years [e.g., *Stocks et al.*, 2002], we found them to be the best available estimates of interannual variability in these regions. For Europe, we obtained country level burned area information after 1987 from the UNECE/TIM bulletins. Prior to 1987 normalized results from the regional fire model Reg-FIRM were used to obtain the variability of burned area south of the Alps, whereas a random fluctuation was added

to the average value of the UNECE/TIM data for regions north of the Alps.

[20] In contrast to some areas in the northern midlatitudes and high latitudes, there are no consistent long-term observations of fires in the tropics. Since the early work of *Seiler and Crutzen* [1980], *Hao et al.* [1990], and *Andreae* [1991], several studies have attempted to improve the estimates of burned area from tropical savanna and forest fires, and more recently different satellite data products were used for this purpose. In spite of these efforts, there is still little agreement on the actual amount of burning on the different continents at lower latitudes [cf. *Houghton*, 2005; *Ito et al.*, 2007] and only few studies have addressed the interannual variability of tropical fires (see Tables S5, S7 and S9 in Text S1 the auxiliary material). Estimates of global tropical deforestation rates for the 1990s vary between about 9 Mha/a [*Achard et al.*, 2004] and more than 27 Mha/a [*Food and Agriculture Organisation* (*FAO*), 2005]. As noted by *FAO* [2005], there is little consistency between different country reports on deforestation areas. For our inventory, we adopt the values of *Houghton* [2003], who estimate 5.52 Mha for Africa, 4.55 Mha for tropical America, and 5.77 Mha for tropical Asia. Trends for earlier years were estimated based on semiquantitative information from various sources.

[21] Burned area estimates for tropical savanna regions were taken from the recent literature. We selected those studies, which present the most detailed analysis and are based on higher-resolution satellite data sets (see discussion in the auxiliary material). Because of the lack of longer-term data sets on tropical fires, we obtained the interannual variability from the Reg-FIRM model. The variability of Reg-FIRM is comparable to estimates from *Barbosa et al.* [1999] and to the GFED2 inventory of *van der Werf et al.* [2006] (Figure 1). However, the Reg-FIRM and the satellite-derived estimates don't always correlate. For example, Reg-FIRM estimates 1989 to be a low fire year in the Southern Hemisphere, whereas *Barbosa et al.* [1999] find rather large burned areas. Because of calibration issues of the Advanced Very High Resolution Radiometer (AVHRR) data used by *Barbosa et al.* [1999], it is unclear how well these data reproduce the actual fire variability. On the other hand, the Reg-FIRM model produces different biases for different ecosystems (see Figure S6 in the auxiliary material), and this may also lead to suppressed or exaggerated variability signals. Absolute values for burned area in Reg-FIRM differ by factors of 5 (Northern Hemisphere) and 2 (Southern Hemisphere) compared to the values of *Barbosa et al.* [1999]. GFED2 burned areas are in better agreement with the Reg-FIRM results. They are about 30% larger in Northern Hemisphere Africa but agree rather well in the Southern Hemisphere.

[22] For several tropical regions, we also tested the correlation of reported or simulated continental-scale burned areas with the El Niño Southern oscillation (ENSO) index. In most cases, we found no significant correlation, except for Indonesia and continental Southeast Asia, where we used these correlations in order to describe the interannual variability as a fluctuation around the decadal deforestation trends described above. Clearly, the topic of burned area variability merits further research, and it is hoped that the analysis of more recent multiyear satellite data series will contribute new insights here.

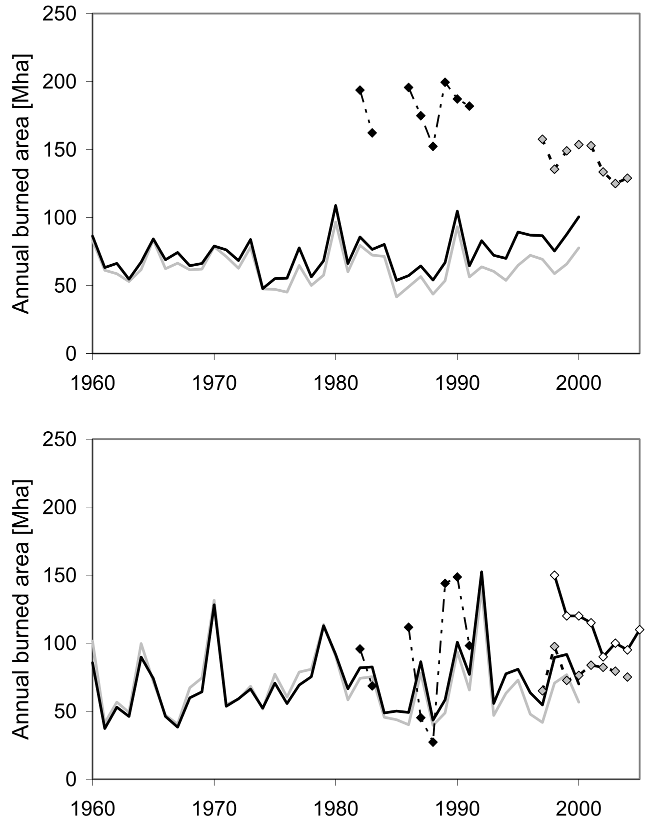

Figure 1. Comparison of burned area estimates for (top) northern and (bottom) southern hemispheric Africa from Reg-FIRM (solid lines) with estimates from *Barbosa et al.* [1999] (dash-dotted line), *van der Werf et al.* [2006] (dashed line), and *Ito et al.* [2007] (solid line with symbols). The solid black line is the standard Reg-FIRM run as described in this paper; the gray line are results from a Reg-FIRM simulation with fixed number of fire ignitions, i.e., not accounting for changes in the population density. The data from *Barbosa et al.* [1999] and *Ito et al.* [2007] were scaled by a factor of 0.5 for clarity.

2.5. Net Average Direct Carbon Emissions

[23] Estimates for the average direct carbon emission per unit area E_{net} were obtained from extensive evaluation of previous studies (see the auxiliary material). Generally, preference was given to those studies, which contained the most detailed treatment of fuel loads and burning characteristics. Table 2 presents a summary of $E_{net}(C)$ values and lists the average attribution of burned areas to the three fire-affected ecosystem classes defined above. For India the literature values had to be significantly reduced in order to achieve consistency with reported emissions from the subcontinent.

[24] Primary and secondary tropical forests have very different fuel loads and combustion behavior, but with the available data it is difficult to distinguish between burns in these two forest types. The use of average fuel load values

Table 2. Net Average Carbon Emissions per Unit Area and Average Distribution of Burned Areas Among the Aggregate Ecosystem Classes[a]

Region	EF*(C), t C/ha			Comment[b]	References
	Forest	Wooded	Grass		
Alaska	25 (80%)	15 (20%)	–		*French et al.* [2002] and *Kasischke et al.* [2005]
Canada	15 (100%)	–	–		*Amiro et al.* [2001] and *Kasischke et al.* [2005]
Siberia + Mongolia	20–25 (68%)	10–15 (19%)	3 (13%)	A	*Soja et al.* [2004]
Contiguous US	10 (40%)	5 (60%)	–		*Kasischke et al.* [2005]
Europe	5–20 (100%)	–	–	B	*Kasischke et al.* [2005]
Central America	43 (100%)	–	–		*Achard et al.* [2004] and *Ito and Penner* [2004]
South America	35 (16%)	20 (67%)	2 (17%)	C	*Achard et al.* [2004], *van der Werf et al.* [2003], and *Hoelzemann et al.* [2004]
NH Africa	25 (3%)	4 (58%)	1.5 (39%)	D	*Achard et al.* [2004], *Barbosa et al.* [1999], and *Ito and Penner* [2004]
SH Africa	–	5 (60%)	1.5 (40%)		*Barbosa et al.* [1999] and *Ito and Penner* [2004]
India	2.5 (10%)	1.5 (90%)	–	E	*Hoelzemann et al.* [2004]
Continental SE Asia	30 (90%)	4 (5%)	1.5 (5%)		*Achard et al.* [2004], *Ito and Penner* [2004], and *Heald et al.* [2004]
Indonesia	54–98 (53%)	–	19 (47%)	F	*Page et al.* [2002], *Christian et al.* [2003], and *Heil et al.* [2006]
Australia	15 (1%)	2.5 (30%)	2.5 (69%)		*Hurst et al.* [1994] and *Russell-Smith et al.* [2003]

[a]Values in parentheses indicate the average distribution of burned areas among the aggregate ecosystem classes.

[b]Comment A, burned areas were provided for forests and "other landscapes"; the wooded fraction of other landscapes is assumed as 60%; 70% of the annual burned area is distributed south of 60°N; the larger carbon consumption values are used for years with total burned area exceeding 3 Mha; comment B, lower value for regions south of 46°N; comment C, based on the assumptions of 33% combustion completeness [*Ito and Penner*, 2004] in 43% tropical forests with average fuel load of 186 t C/ha and 57% other forests with 47 t C/ha [*Achard et al.*, 2004]; comment D, based on the assumptions of 33% combustion completeness [*Ito and Penner*, 2004] in 36% tropical forests with average fuel load of 143 t C/ha and 64% other forests with 36 t C/ha [*Achard et al.*, 2004], comment E, fuel load values adjusted in order to yield reasonable emission fluxes; comment F, lower value for fragmented forests and plantations, higher value for undisturbed tropical forest. Fuel load for grasslands includes contribution from crops.

and combustion efficiencies may be misleading. *Houghton* [2005, p. 951] notes "We do not know whether tropical deforestation occurs in forests of high-, low-, or average biomass." Inverse modeling studies for carbon monoxide [*Pétron et al.*, 2004; *Arellano et al.*, 2004] indicate relatively large emissions from tropical forest areas. However, the results from these two studies are not always in agreement with each other (see Table 6 in section 3.2).

2.6. Seasonal Fire Patterns

[25] Seasonal variations of burned area were mostly obtained from the GBA2000 satellite data product [*Tansey et al.*, 2004], which was processed in GWEM in order to derive specific seasonality maps for the three aggregate ecosystem classes and to filter fires in agricultural areas. We note, however, that GBA2000 severely underestimates the burned area in South America, and GWEM 1.4 therefore uses a different data set for this region (K. Longo, personal communication, 2004). This data set is based on a combination of AVHRR and GOES/ABBA satellite derived fire pixels (http://www.cptec.inpe.br/queimadas/). These are converted to burned area as described by *Prins et al.* [1996, 1998].

[26] For Indonesia, four different seasonality profiles were determined based on an analysis of AVHRR fire retrievals for different ENSO signatures (see the auxiliary material for details). At high latitudes, an average seasonal profile was derived from a literature review [i.e., *Stocks et al.*, 2002; *Kasischke et al.*, 2005], because fires in the boreal regions are too sparse to derive a robust seasonal map based on satellite observations of a few individual years. More details on the definition of the seasonality patterns can be found in the auxiliary material.

2.7. Geographical Distribution of Fires

[27] In order to be used as emission inventory for global modeling purposes, the regional emission estimates must be distributed in space and time. Except for Canada, where we could make use of explicit coordinates and dates for large fire events, no detailed information on fire occurrence from 1960 to 2000 is available. We therefore had to develop a methodology for creating a "plausible fire distribution." The underlying idea of this effort was to artificially create "virtual" fires, which should reproduce the general burning patterns and fire density in individual regions at least when analyzed on the relatively coarse grid scales of present models.

[28] In the middle and higher latitude forests predominantly of the Northern Hemisphere fires recur on intervals of several years to decades [cf. *Thonicke et al.*, 2001]. Individual large-scale fires are dominating and there is low probability that the same area (e.g., the same grid box) is affected by fire in two consecutive years. This general feature is confirmed by multiannual satellite imagery of fires from different sensors [cf. *Sukhinin et al.*, 2004; *van der Werf et al.*, 2006]. In contrast, tropical savanna fires are typically much smaller and numerous and their return interval is on the order of 1 year. As a consequence the same area (on the scale of a grid box) can be affected by fires every year. We take this different behavior into account by applying different methodologies for the geographical distribution of fire events.

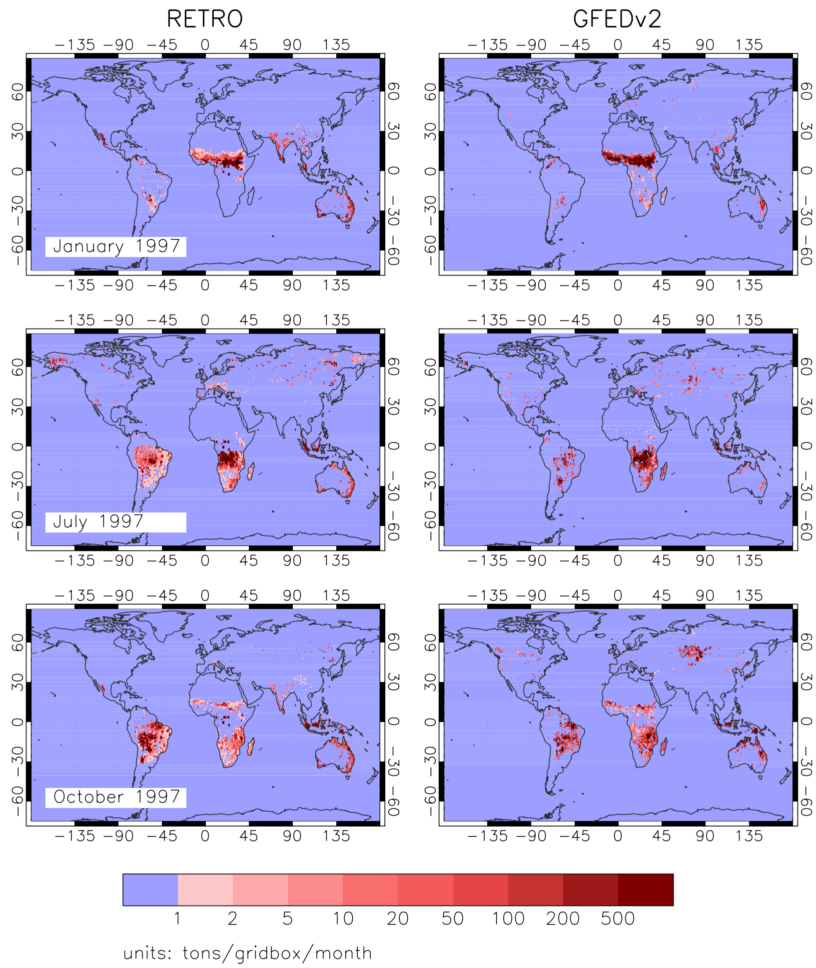

Figure 2. Comparison of monthly average total carbon emissions from (left) the RETRO inventory and (right) the GFED version 2 inventory for selected months of the year 1997.

[29] In the extratropical latitudes (and for tropical deforestation) we distribute individual fires by means of a two-step random process. In the first step, three size distributions of individual fires were generated from the annual burned area estimates for the three fire-affected ecosystem classes. Since this process is repeated for every year of the emission inventory, the number of fires will also vary. We used a lognormal distribution with a width σ of 1.5, 1.0, and 0.7 for "forest", "wooded", and "grass" fires, respectively. Using the Canadian LFDB we verified that the lognormal distribution yields a reasonable fit to the fire size distribution. Future versions of the inventory could perhaps replace this with a tapered Pareto distribution which was shown to more accurately reflect the size distribution for fires in California [*Schoenberg et al.*, 2003]. The average area per fire was adjusted to yield a fire density comparable to satellite data products when viewed on the final 0.5° grid (Figure 2). The fire sizes listed in the auxiliary material should be treated as a parameter value rather than an estimate of the real average fire size.

[30] In the second processing step, the individual virtual fires were distributed among all grid boxes of the respective ecosystem type within the region and across all months of the fire season. In order to allow for some less-than-continental-scale variability we weighted the probability for placing a fire in a specific 0.5 × 0.5° grid box with the monthly mean fire danger index (FDI) computed by Reg-FIRM. This was done for the boreal zone, for Australia, and for deforestation fires in continental Southeast Asia. The calculation of FDI is described in the auxiliary material.

[31] While this approach does not generate exact fire sizes and locations, it reproduces the general distribution of fires fairly well (see Figure 2). Furthermore, this method reflects the random nature of real fires, which may be important if the fire emissions from this inventory are used in a carbon cycle model with feedbacks on the vegetation cover.

[32] In tropical savanna regions, where the number of fires is very large and burning recurs annually, a monthly geographical distribution based on GBA2000 and GWEM 1.4 was used. However, the burned area in each grid box was allowed to vary by up to 30% which was achieved by adding random noise to the GBA2000 distribution. The processing ensured that the total burned area on the continental matched the precomputed value which was generally obtained from the Reg-FIRM model (Table 1). For Indonesia, separate fire maps were obtained from an independent analysis of AVHRR data. As for the seasonality profiles, four typical

Table 3. Summary of Average Burned Areas and Total Carbon Emissions for the 13 Regions of the RETRO Vegetation Fire Inventory

Region	Burned Area, 10^6 ha	Total Carbon Emissions, Tg C/a	Minimum Year	Maximum Year	Percent Contribution to Global Emissions
Alaska	0.2 (0.01–1.23)	3.8 (0.2–23.0)	1978	1990	0.18 (0.01–0.95)
Canada	1.9 (0.17–7.54)	24.2 (2.5–90.8)	1963	1995	1.15 (0.15–4.48)
Siberia + Mongolia	4.1 (1.13–15.0)	62.5 (16–292)	1974	1998	3.01 (0.61–9.62)
Contiguous US	1.4 (0.21–3.01)	9.4 (1.3–19.9)	1991	2000	0.49 (0.05–1.26)
Europe	0.5 (0.19–0.91)	2.6 (1.3–5.3)	1963	2000	0.13 (0.05–0.24)
Central America	1.4 (0.31–3.15)	58.8 (13–135)	1966	1998	2.78 (0.67–5.85)
South America	27.9 (16.7–42.6)	548 (340–808)	1964	1993	26.80 (16.07–35.98)
NH Africa[a]	136 (88–199)	503 (342–729)	1974	1990	24.75 (17.67–33.26)
SH Africa	133 (71–291)	490 (261–1067)	1961	1992	23.49 (12.12–36.54)
India	18.1 (13.4–22.0)	27.9 (20.6–33.8)	1961	1976	1.40 (0.67–2.12)
Continental SE Asia	1.7 (0.20–4.20)	44.7 (3.1–116.1)	1971	2000	2.11 (0.21–5.15)
Indonesia	–	135 (14–1136)	1975	1997	5.46 (0.78–36.92)
Australia	57 (27.8–97.4)	169 (83–295)	1968	1980	8.25 (4.59–16.41)
Global	383 (273–567)	2078 (1410–3139)	1974	1992	100.0

[a]Including tropical deforestation (1.3–5.5 Mha/a; 34–139 Tg C/a).

fire distributions were compiled for four ENSO classes (strong El Niño, weak to normal El Niño, neutral, and La Niña; for details, see the auxiliary material) based on a cleaned version of the multiyear time series of active fires from the European Space Agency's World Fire Atlas [*Mota et al.*, 2006].

3. Results and Discussion

3.1. Global and Regional Carbon Emissions

[33] On average, the RETRO fire inventory estimates a global total direct carbon emission flux from wildland fire emissions of 2078 Tg C/a. Minimum emissions occurred in 1974 (1410 Tg C/a), and maximum emissions were derived for the year 1992 (3140 Tg C/a).

[34] Table 3 summarizes the mean results and extreme values from this study for the individual world regions. On average, the African continent contributes about one half of the global vegetation fire emissions, South America contributes a quarter, and Australian fires are responsible for almost 9% of global carbon emissions from open burning of vegetation. The temperate and boreal regions contribute about 5% on average, but their contribution can be as high as 12% (e.g., the contribution from the Siberian fires in 1998). The single largest regional contribution to the global wildland fire emissions stems from the Indonesian peat forest fires in 1997. Globally, 1997 ranks second with 3077 Tg C/a. According to our inventory, maximum fire activity for Africa took place in 1992, and in South America in 1993.

[35] There are very little data to validate these results. Some indications of the interannual variability of smoke emissions can be obtained from variations in the TOMS aerosol index [cf. *Duncan et al.*, 2003; *Ito and Penner*, 2005b], but this remains semiqualitative (see discussion in section 3.3). Inverse modeling studies, for example for carbon monoxide, have usually been performed for a single year only. Furthermore, these studies still have difficulties to separate vegetation fire emissions from other sources and to distinguish clearly between model errors and errors in the a priori emission estimates (see section 3.2).

[36] Table 4 compares the average global carbon emissions from different inventories with the results from our study. A more detailed comparison of annual regional emission estimates from our inventory with the *van der Werf et al.* [2006] study can be found in the auxiliary material (Tables S2, S7 and S9 in Text S1). The literature values for global direct carbon emissions from wildland fires range from 1428 Tg C/a [*Ito and Penner*, 2004] to 2771 Tg C/a [*Galanter et al.*, 2000]. The RETRO inventory is located near the center of these estimates. While the early study of *Seiler and Crutzen* [1980] attributed almost two thirds of the global emissions to tropical forest fires, and less than one third to savanna fires, this ratio has since been reversed, and all newer studies agree on the dominant importance of savanna fires for carbon emissions. Their emissions are generally estimated between 1200 and 1600 Tg C/a, and the estimate from our inventory falls within this range (mean value of 1399 Tg C/a). The estimates from tropical forest fires disagree by a much wider margin (600–900 Tg C/a if we exclude the early estimate by *Seiler and Crutzen* [1980]). The RETRO inventory yields an average value of 727 Tg C/a for emissions from tropical forests during the 1990s and produces much lower emissions during the 1960s and 1970s (see Figure 5). Further discussion on the emission trends in our inventory can be found in section 3.4.

[37] Carbon emissions from forest fires in temperate and boreal regions (average 102 Tg C/a, range 33–366 Tg C/a) agree well with estimates from *Lavoué et al.* [2000], who give a range of 30–315 Tg C/a. A large fraction of these emissions stems from fires in Siberia and Mongolia where we have only little reliable quantitative information available (see detailed discussion in the auxiliary material). The estimated average emissions from temperate and boreal fires by *Andreae and Merlet* [2001], 288 Tg C/a, is significantly higher than our estimate. Their estimate is based on the study of *Lobert et al.* [1999], which uses statistical data for the 1980s.

[38] The geographical distribution and seasonal pattern of fires agrees reasonably well with the results obtained by *van der Werf et al.* [2006] in the GFED version 2 inventory which is based on MODIS satellite data (Figure 2). The most obvious discrepancies between the two inventories can be observed for the boreal region in winter, where fires are absent in the RETRO inventory (due to the prescribed seasonal pattern) while some fire activity is included in the GFED version 2 inventory. Upon closer inspection, more differences become apparent, but overall both inventories

Table 4. Comparison of Annual Direct Total Carbon Emissions From Wildland Fires

Study Period	Carbon Emissions, Tg C/a			Reference
	Tropical Forest	Savanna	Global	
1970s	1090	536	1760	*Seiler and Crutzen* [1980][a]
1970s	373	1400	1932	this study
1980s	570	1660	–	*Hao et al.* [1990][a]
1980s	910	1335	–	*Hao and Liu* [1994]
1980s	365	1410	2071	*Lobert et al.* [1999][b]
1980s	570	–	–	*DeFries et al.* [2002][c]
1980s	608	1345	2137	this study
1990s	748	1171	2771	*Galanter et al.* [2000]
1990s	600	1422	2310	*Andreae and Merlet* [2001]
1990s	910	–	–	*DeFries et al.* [2002][c]
1990s	–	–	2240	*Houghton* [2003][c]
1990s	857[d]	1566	2423	*Yevich and Logan* [2003]
1990s	873[d]	1607	2480	*Bond et al.* [2004][a]
1990s	–	–	840–2240[e]	*Houghton* [2005][c]
1990s	727 (487–1534)	1559 (1295–2166)	2531 (2152–3139)	this study
2000	–	–	1428	*Ito and Penner* [2004]
2000	–	–	1741	*Hoelzemann et al.* [2004]
2000	–	–	2038	*van der Werf et al.* [2006]
2000	510	1499	2254	this study
1997–2001	–	–	2096	*van der Werf et al.* [2003]
1997–2004	–	–	2460 (2038–3183)	*van der Werf et al.* [2006]
1960–2000	–	–	2419[f]	*Lavoué et al.* [2000]
1960–2000	489 (164–1534)	1399 (995–2166)	2078 (1410–3139)	this study

[a]Values derived from estimate of combusted biomass using a carbon content of 45%.
[b]Total derived from Lobert et al.'s Table 1 without categories WDF, CMB, SBS, and BIF.
[c]Study gives net carbon flux instead of direct emissions.
[d]Including extratropical forests.
[e]Sensitivity study using different deforestation and biomass estimates. Lowest value obtained with deforestation rates from *DeFries et al.* [2002]; largest value from *Houghton* [2003]. Deforestation rates from *Achard et al.* [2004] would yield 1340 Tg C/a.
[f]Inventory of *Liousse et al.* [1996] for tropical fires. Includes agricultural and domestic fires.

should yield rather similar results when used in global modeling studies.

3.2. Trace Compound Emissions

[39] Emissions of a total of 27 trace gases and aerosol compounds were computed from the total carbon emissions in a postprocessing step. Average results for selected compounds are shown in Table 5. The carbon emissions from the "forest", "wooded", and "grassland" classes were each multiplied with emission factors from *Andreae and Merlet* [2001] with updates from M. O. Andreae (personal communication, 2005), and from *Christian et al.* [2003] and O. Schmidt (personal communication, 2004) for peat fires. Seasonal changes in emission factors due to varying fuel moisture and litter amounts were ignored.

[40] Peat fires are generally of smoldering type and thus emit large amounts of reduced compounds and relatively little amounts of fully oxidized species such as CO_2 and NO_x. We used the FAO World Reference Base for Soil Resources [*FAO*, 2003] in order to identify geographical regions where peat burning (or generally burning of soils with high organic content) is likely. The WRB soil map contains 30 reference soil groups, and three of these include a classification as histosols (organic soils). All grid boxes with a histosol fraction of at least 5% were labeled as "peat region", and the emission factor was assigned as mean value of the emission factor from peat burning and the respective ecosystem-type emission factor from *Andreae and Merlet* [2001]. Indonesian peat fires were treated separately (see section on Indonesia in the auxiliary material).

[41] Table 6 summarizes recent regional and global emission estimates for carbon monoxide from wildland fires. There is a wide scatter between different studies even if they are based on similar input data. For example, *Ito and Penner* [2004] and GWEM 1.4 are both based on GBA2000 for burned area but they differ in the allocation of fuel loads to ecosystem classes and in their estimates of the combusted fraction. Also, the two inverse modeling studies of *Pétron et al.* [2004] and *Arellano et al.* [2004], which are both using data from the MOPITT instrument on board the TERRA

Table 5. Average Global Annual Emissions of Selected Trace Compounds

Species	Average Annual Emissions, Tg/a			
	1960s	1970s	1980s	1990s
CO_2	5728	6629	7307	8650
CO	250	296	347	417
NO_x	12.3	14.1	15.4	18.3
BC	1.69	2.00	2.29	2.72
OC	13.3	15.7	18.5	22.4
CH_4	10.7	13.2	16.7	20.4
H_2	4.79	6.11	7.86	9.42
CH_2O	2.94	3.47	4.09	4.94
CH_3CHO	1.89	2.21	2.55	3.06
CH_3OH	5.86	6.93	8.17	9.83
Ethane	1.58	2.00	2.57	3.09
Propane	0.75	1.06	1.54	1.85
Ethene	3.55	4.32	5.23	6.27
Propene	1.76	2.22	2.90	3.51
Acetone	1.92	2.25	2.58	3.07
NH_3	3.66	4.17	5.19	6.48
SO_2	1.64	1.90	2.27	2.80

satellite do not agree with each other. In particular, they differ by a factor of 3.8 for South American emissions. This is a consequence of different assumptions about errors in the inverse modeling procedure and may also reflect specific model biases. The estimates from inverse modeling include vegetation fire emissions as well as biofuel and fossil fuel emissions and should thus be regarded as upper limit when comparing to the RETRO vegetation fire emissions.

[42] The RETRO estimates generally fall within the range of previous studies with the exception of the Siberian emissions of 1987 and 2000, which are significantly lower than what was found in other studies, although the average total CO emissions for the boreal region agree well with the *Kasischke et al.* [2005] estimate. We would like to point out that Southeast Asian emissions are extremely uncertain and the different estimates vary by more than a factor of 5 even if the extreme fires during the strong El Niño 1997/1998 are not considered (for further details, see the auxiliary material). For Indonesia it has been found that peat burning contributes a large fraction of fire emissions (the CO emission factor for peat is about twice as large as that of tropical forest burning), yet peat fires have not been explicitly considered in most of the previous studies. A more thorough discussion of different inventories for the year 2000 [*Hoelzemann*, 2006] confirms the finding of this study that a given inventory's low bias in some regions may sometimes be compensated by a high bias in other regions so that a simple comparison of global average values can hide important differences.

[43] Mean global annual emission estimates for black carbon (BC) and organic carbon (OC) are 2.2 and 17.6 Tg C/a, respectively (ranges 1.5–3.6, and 11.5–28.9 Tg C/a; see Table 5). These values are lower than other recent literature values (Table 7), but they also cover a longer time period. Our estimate of 2.7 Tg/a for the 1990s agrees well with recent estimates of *Dentener et al.* [2006] and *van der Werf et al.* [2006]. Most of the literature estimates fall in the range of 3–5 Tg/a for BC, and they typically report OC emissions between 23 and 35 Tg/a. There is considerable debate about suitable emission factors for BC. The *Andreae and Merlet* [2001] values are considerably lower than what was used in the studies of *Cooke and Wilson* [1996], *Liousse et al.* [1996], or *Chin et al.* [2002]. If we adjust the results from these studies to the *Andreae and Merlet* [2001] emission factors, the spread is considerably reduced (Table 7, adjusted BC values), and the RETRO results are consistent with most other inventories. We point out that some of the other studies include agricultural residue burning which is absent from our inventory and would contribute about 10% to the total BC emissions [cf. *Bond et al.*, 2004].

3.3. Interannual Variability

[44] One of the most important reasons for constructing the RETRO inventory in the manner described in this paper was the necessity to provide some estimate of interannual variability of fire emissions in order to attempt a reproduction of the variability of trace gas concentrations in the RETRO modeling work. Figure 3 summarizes the annual total direct carbon emissions in the form of a bar chart, so that the regional contributions can be distinguished. The magnitude of global wildland fire emissions spans a factor of 2 (see also Table 4) and makes it difficult to visually discern a long-term trend signal. Most of the variability in the global emissions comes from variations in South America and Indonesia.

[45] As clearly shown by Figure 3, the RETRO inventory reproduces a number of specific major fire events, such as Indonesia in 1997 and Indonesia, Siberia, and Central America in 1998. During these episodes, the above mentioned regions contribute 45%, 13%, 12%, and 4%, respectively to the global carbon emissions of that year. It is useful to discuss a few outstanding features from the *Duncan et al.* [2003] time series and compare them with the results from our analysis. According to the *Duncan et al.* [2003] study, years with high fire activity in Canada and Alaska were 1981, 1988, 1989, 1998, and 2000, and higher than average activity was reported also for 1984, 1987, and 1999 (note that there is a gap in the TOMS AI time series between 1993 and 1996; see Duncan et al.'s Figure 8). In our inventory, the 10 years with highest emissions from this region are (in descending order): 1995, 1994, 1989, 1981, 1980, 1998, 1979, 1991, 1990, 1988. Thus, four out of five high fire years in the *Duncan et al.* [2003] inventory are also ranked as top fire years in our inventory. Discrepancies are observed for the year 2000 (high fire year of *Duncan et al.* [2003] and below-average year in the RETRO inventory, and for 1984 and 1987 (above-average fire activity of *Duncan et al.* [2003] and below-average activity in our inventory). It is unclear where these differences originate from. Some confidence in our results can be gained from a comparison with the *van der Werf et al.* [2006] study. According to their inventory, the ranking of years according to the largest carbon emissions from Canada and Alaska between 1997 and 2000 is 1998, 1999, 1997, and 2000. This is exactly the ranking which we find in our inventory as well.

[46] In "Asiatic Russia," 1986 and 1998 stand out as the years with largest fire activity in the *Duncan et al.* [2003] study, followed by 1985 and 1987 and then 1984 and 1996. In the RETRO inventory, 1998 is first, followed by 1996. The year 1986 ranks eleventh and 1987 ranks thirteenth. The year 1984 is reported as below-average, while 1990, 1993, 2000, and 1989 all rank higher than 1986. The *van der Werf et al.* [2006] study only confirms that 1998 was a high fire year, while 1999 and 1998 had medium-to-high emissions, and 1997 ranks rather low, in agreement with both our inventory and the *Duncan et al.* [2003] study. The year 1986 had been reported as a year with exceptionally high fire activity [cf. *Goldammer et al.*, 2003] in the boreal Asian region, and this does not seem to be adequately reflected in the RETRO inventory. A lot of the 1986 fires occurred along the Russian-Mongolian border, where aerial surveillance is low. Furthermore, we did not have any burned area estimates for Mongolia available, which in this case may have led to a substantial underestimate of the emissions. In summary we must conclude that all estimates of the interannual variability of fire emissions from boreal Asia remain very uncertain.

[47] The *Duncan et al.* [2003] time series show only few distinct features in the tropical regions which are amenable to a qualitative discussion. For Indonesia and Malaysia, one

Table 6. Summary of Annual Mean CO Emission Estimates From Open or Wildland Fires

Study Period	CO Emissions[a]	Reference
	Boreal North America	
1950–1999	0.1–13[b]	*French et al.* [2002]
1960–2000	7 (1–26)	this study
2000	33	*Hoelzemann et al.* [2004]
2000	11	*Hoelzemann* [2006] (GWEM 1.4)
2000	4	this study
	Greater Siberia	
1960–2000	15 (4–71)	this study
1998–2002	43–80	*Soja et al.* [2004]
1998–2000	13–71	this study
1987	36	*Cahoon et al.* [1994]
1987	20	*Duncan et al.* [2003]
1987	15	this study
2000	51	*Hoelzemann et al.* [2004]
2000	71	*Hoelzemann* [2006] (GWEM 1.4)
2000	25	this study
	Total Boreal	
1960–2000	22 (5–88)	this study
1991, 1995–2003	33–77	*Kasischke et al.* [2005]
1991, 1995–2000	20–88	this study
1997/1998[c]	57	*van der Werf et al.* [2004]
1997/1998[c]	64	this study
1990s	68[d]	*Andreae and Merlet* [2001]
1990s	35 (16–88)	this study
1998	69	*Duncan et al.* [2003]
1998	88	this study
2000	46	*Ito and Penner* [2004]
2000	10	*Arellano et al.* [2004]
2000	29	this study
	Central and South America	
1960–2000	77 (44–118)	this study
1980–2000	84	B. N. Duncan and J. Drevet (personal communication, 2006)
1980–2000	89 (66–118)	this study
1992	101	*Potter et al.* [2002]
1992	98	this study
1997/1998[c]	138	*van der Werf et al.* [2004]
1997/1998[c]	96	this study
2000	55	*Pétron et al.* [2004]
2000	210	*Arellano et al.* [2004]
2000	29	*Hoelzemann et al.* [2004]
2000	22	*Hoelzemann* [2006] (GWEM 1.4)
2000	18	*Ito and Penner* [2004]
2000	70	this study
	NH Africa	
1960–2000	67 (45–97)[e]	this study
1980–2000	87	*Duncan et al.* [2003]
2000	66	*Pétron et al.* [2004]
2000	105	*Arellano et al.* [2004]
2000	60	*Hoelzemann et al.* [2004]
2000	95	*Hoelzemann* [2006] (GWEM 1.4)
2000	74	*Ito and Penner* [2004]
2000	95	this study
	SH Africa	
1960–2000	72 (37–151)	this study
1980–2000	86	*Duncan et al.* [2003]
2000	66	*Pétron et al.* [2004]
2000	60	*Arellano et al.* [2004]
2000	69	*Hoelzemann et al.* [2004]
2000	96	*Hoelzemann* [2006] (GWEM 1.4)
2000	94	*Ito and Penner* [2004]
2000	68	*Ito et al.* [2007][f]
2000	72	this study

Table 6. (continued)

Study Period	CO Emissions[a]	Reference
	Total Africa	
1982–1999	92–196[f]	*Barbosa et al.* [1999]
1982–1999	151 (104–232)	this study
	Indonesia and Malaysia	
1997/98	170	*Duncan et al.* [2003]
	Southeast Asia and Indonesia	
1960–2000	41 (4–256)	this study
1980–2000	118	*Duncan et al.* [2003]
1997/1998[c]	300	*van der Werf et al.* [2004]
1997/1998[c]	306	this study
2000	110	*Arellano et al.* [2004]
2000	19	*Hoelzemann et al.* [2004]
2000	18	*Hoelzemann* [2006] (GWEM 1.4)
2000	11	*Ito and Penner* [2004]
2000	37	this study
	Australia	
1960–2000	23 (11–40)	this study
1991	17	*Hurst et al.* [1994]
1991	32	this study
2000	7	*Hoelzemann et al.* [2004]
2000	25	*Hoelzemann* [2006] (GWEM 1.4)
2000	26	this study
	Global	
1960–2000	330 (217–555)	this study
1980–2000	437	*Duncan et al.* [2003]
1980–2000	384 (267–555)	this study
1997–2004	433 (337–591)	*van der Werf et al.* [2006]
1990s	554	*Galanter et al.* [2000]
1990s	345	*Andreae and Merlet* [2001]
1990s	417	this study
1997	557	*van der Werf et al.* [2006]
1997	555	this study
1998	591	*van der Werf et al.* [2006]
1998	514	this study
2000	435–460	*Pétron et al.* [2004]
2000	266	*Ito and Penner* [2004]
2000	271	*Hoelzemann et al.* [2004]
2000	349	*Hoelzemann* [2006] (GWEM 1.4)
2000	552	*Arellano et al.* [2004]
2000	337	*van der Werf et al.* [2006]
2000	359	this study

[a]CO emission estimates are in Tg (CO)/a.
[b]Alaska only.
[c]August 1997 through September 1998.
[d]All extratropical forest.
[e]Estimates provided for individual years from 1998 to 2005. Mean value 60 Tg/a.
[f]High estimate.

can observe a clear correlation with the ENSO signal, which we have explicitly modelled in our inventory, and which is consistent between the two studies (see also Figure S12 in the auxiliary material). In Central America, 1998 stands out as an extreme fire year in the work by *Duncan et al.* [2003]. This is consistent with the results from the work presented here, although the magnitude of the enhancement appears somewhat smaller in our study (see also Figure S9 in the auxiliary material).

[48] Much of the interannual variability in our inventory is derived from the Reg-FIRM model results and its variability in turn is largely driven by changes in the fire danger index (FDI). As mentioned above, FDI has been computed from CRU meteorological data. Hence, the question arises as to how accurately the CRU data reflects the interannual variability of these fields over time, particularly in remote areas where the meteorological observation network is sparse. Changes in wind speed (acting on fire rate of spread and thus area burnt) and population density (which drives human-caused ignition rates) are other possible sources uncertainty in the fire model. The current formulations in the fire model for fire spread and human-caused ignitions are simplified, and need to be improved in future versions of Reg-FIRM. For example, the effect of changes in wind speed on fire spread rates is currently simulated as a simple linear step-up function [*Venevsky et al.*, 2002]. However, other studies report fire spread rates as being

Table 7. Comparison of Different Global Black Carbon Emission Estimates From Open Fires[a]

Study Period	BC, Tg/a Original	BC, Tg/a Adjusted	OC, Tg/a	Comment[b]	Reference
1960–1990	3–4	1.7	27	A	*Ito and Penner* [2005b]
1960–2000	2.2	2.2	17.6		this study
1980s	6.0	2.0	–	B	*Cooke and Wilson* [1996]
1980s	4.1	1.5	24.7	C	*Liousse et al.* [1996]
1980s	2.3	2.3	18.5		this study
1990s	3.3	3.3	25.0	D	*Bond et al.* [2004]
1990s	2.7	2.7	22.4		this study
1990, 1996, 1997	11.0	2.9	77	E	*Chin et al.* [2002]
late 1990s	3.0	3.0	24.8	F	*Dentener et al.* [2006]
1997–2004	2.9	2.9	23.9		*van der Werf et al.* [2006]
1997–2000	2.9	2.9	23.9		this study

[a]Original values are the published estimates, adjusted values were obtained by applying emission factors for tropical forest and savanna burning from *Andreae and Merlet* [2001], to the published values, thereby assuming that 2/3 of the total combusted dry matter is burned in savanna fires.

[b]Comment A, values taken from Figure 2 of *Ito and Penner* [2005b], inventory was derived after scaling the bottom-up inventory of *Ito and Penner* [2004], to estimates from the inverse modeling study of *Arellano et al.* [2004]; average scaling factor was 2.1, but scaling factors of 9–20 were applied for tropical forest areas; adjusted value reflects likely estimate from bottom-up inventory and should be regarded as a lower limit. Comment B, tropical fires only, EF = 1.0–2.2 g/kg DM for all ecosystems. Comment C, tropical fires only (without agricultural and biofuel burning), adjustment calculated after adding 0.4 Tg BC from extratropical forest fires [*Lavoué et al.*, 2000], EF = 1.53 g/kg DM for forests and 0.81 g/kg DM for savannas. Comment D, includes agricultural residue burning, inventory based on compilation of statistical information. Comment E, based on *Duncan et al.*'s [2003] inventory, includes agricultural residue burning, EF = 2 g/kg DM for all ecosystems; a newer version of this inventory was compiled with EF = 1 g/kg DM and yields a total of 5.06 Tg BC emissions (M. Chin, personal communication, 2006). Comment F, based on the GFED version 1 inventory of *van der Werf et al.* [2003]; emission factors taken from *Andreae and Merlet* [2001], they list POM instead of OC and give a conversion factor of POM = 1.40 × OC.

nonlinearly related to wind speed [*Pyne et al.*, 1996; *Finney*, 1998].

3.4. Global Trend of Wildland Fire Emissions

[49] Figure 4 shows the decadal mean trends of CO_2 and CO emissions from wildfires in six selected world regions and globally. Our results suggest that CO_2 emissions increased by about 50% over the past 4 decades whereas CO emissions almost doubled. This increase is largely driven from the trend in deforestation rates. During the 1960s and 1970s the strongest increase occurred in Africa and South America. After about 1970 we note a strong rise in Southeast Asian deforestation fire emissions. It is very difficult to obtain reliable quantitative information about these changes. Official statistics often ignore illegal logging or focus only on forest plantations. Because of their normally small size, deforestation fires also present a particularly challenging problem to remote sensing. Boreal and temperate forest fires exhibit a positive trend of about 50% over Asia and 100% over North America in our inventory, but these trends contribute relatively little to the global trend in CO_2 or CO emissions. It seems as if the chosen period from 1960 to 2000 represents an extended period of relatively little fire activity in these ecoregions.

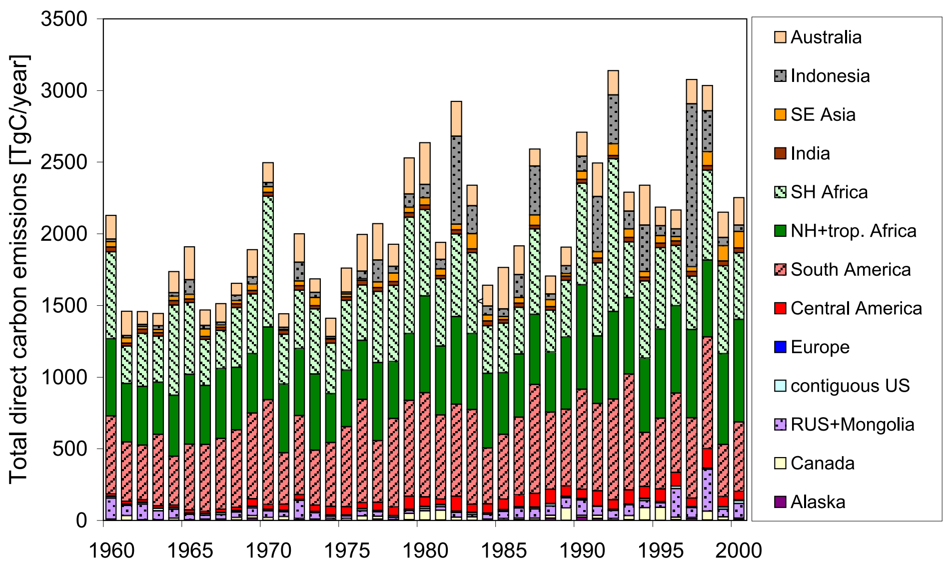

Figure 3. Time series and regional contributions of total direct carbon emissions from wildfires from 1960 to 2000.

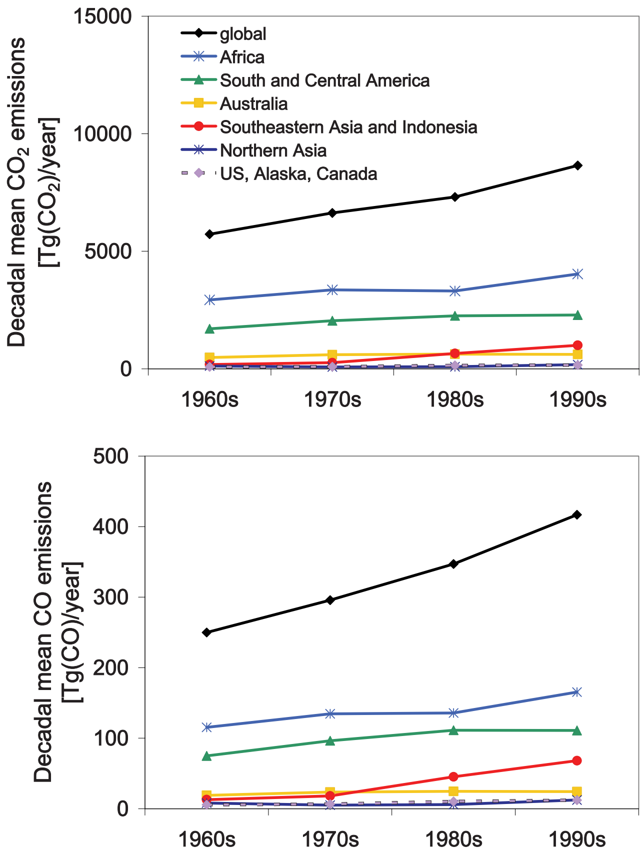

Figure 4. Decadal trends in (top) CO_2 and (bottom) CO emissions from wildfires in different world regions.

Studies of boreal fire emissions over the past century or so [cf. *Mouillot and Field*, 2005; *Ito and Penner*, 2005b] have indicated that fire activity in the northern midlatitudes to high latitudes showed a strong decline after the end of the 19th century. Other studies of the more recent past are consistent with our inventory and indicate that emissions from boreal fires have been rising since the 1960s [*Kasischke and Turetsky*, 2006] and in particular since the late 1990s [*van der Werf et al.*, 2006], possibly due to climate change in these regions.

[50] As mentioned in section 2, the inventory presented here focuses exclusively on open burning and excludes the domestic use of biofuels as well as small-scale agricultural residue burning. These emissions and their historical trends are described in a different inventory of the RETRO project [*Pulles et al.*, 2007]. In Figure 5 we compare the global annual mean CO emissions from these sources with the CO emissions from forest fires and from fires in other ecosystems. Residential burning emissions roughly parallel the trend in forest fires derived from this study but are offset by about 70 Tg (CO)/a. The trend in savanna and grassland fires is much smaller and we also find no significant trend in agricultural burning, which overall has a smaller contribution to global CO emissions. Closer inspection of the agricultural burning data shows that a slightly increasing trend in Africa, Latin America, Southeast Asia and the Middle East is balanced by a strong decline of agricultural burning emissions in Europe.

[51] The fact that there is only a weak trend for savanna fire emissions in the RETRO inventory is largely owing to the fact we have not included an analysis of land-use change in our study. In particular for Africa there are two competing factors, which may or may not balance each other: on the one hand, population density increased throughout the past 40 years, and more people will generally ignite more fires and thus increase the annual burned area. On the other hand, large areas of formerly natural savanna were converted to farmland, which reduces the area that is labeled "wildland" and increasing population pressure also leads to larger consumption of fuel for grazing or as fire wood (which would be labeled residential biofuel burning in our inventory). Furthermore, the fire size distribution and other fire properties may have changed leading to either enhanced or reduced emissions. Such changes can occur on rather small scales and are therefore almost impossible to quantify. Imagery from the early period of Landsat may be of use in this respect, but their analysis is rather laborious and would require substantial resources. On the basis of our subjective interpretation of the available information we would estimate that wildland fire emissions in the 1960s were at least half of the present-day value and almost certainly not higher than today.

[52] In general, our trend estimates agree qualitatively with the analysis of *Mouillot and Field* [2005], who constructed decadal estimates of carbon release from fires from 1900 to 2000 based on regional and country statistics. They also agree with the study of *Ito and Penner* [2005b]. In contrast, *Houghton* [2003] estimates a strong increase in the global net carbon release between 1960 and 2000, which he attributes to the strong deforestation trend. Here one has to be aware that savanna fires are not accounted for in the *Houghton* [2003] study, because the carbon released from these fires will be absorbed by the terrestrial ecosystem again when it grows back. In agreement with our study,

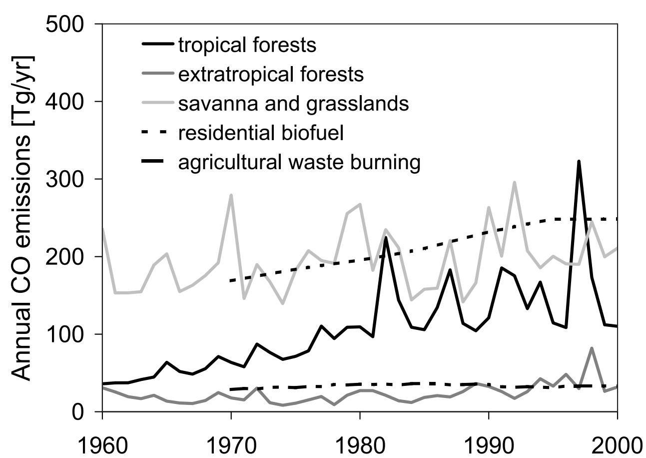

Figure 5. Global trends in CO emissions from domestic biofuel use and agricultural residue burning taken from the RETRO anthropogenic inventory compared to CO emissions from forests and other vegetation from this study.

Mouillot and Field [2005] also find a rather stable amount of savanna burning in Africa and South America, a slightly decreasing trend for savanna fires in Australia, a strong increase of fires in Southeast Asia, and an increase of boreal fires in North America. In contrast to our results their maximum burned area in Northern Asia is found in the 1980s, whereas we find the maximum in the 1990s in agreement with the recent studies using satellite retrievals of fire hot spots or burned areas. Other differences can be diagnosed for Europe: *Mouillot and Field* [2005] report a strong increase between 1960 and the 1980s, whereas our inventory only shows a very weak trend, consistent with recent analysis of Landsat scenes for Portugal (J. M. C. Pereira, unpublished material, 2006).

[53] The differences in the relative rise of CO_2 and CO emissions is consistent with the increasing fraction of forest burning over the past four decades and exacerbated by increasing amounts of organic soil burning in Indonesia and elsewhere.

4. Conclusions

[54] This study has undertaken a critical review of the available literature reporting on the emissions of carbon and several trace species from wildland fires. We collected quantitative and semiquantitative information from a large amount of different sources and adopted a simplified approach to estimate annual total direct carbon emissions for the time period from 1960 to 2000. We used the available information to construct the first detailed gridded inventory of global wildland fire emissions over such a long period. Our approach minimizes errors which arise due to the correlation between the different parameters of the classical fire emissions equation and it allows for meaningful comparisons between more detailed studies for various geographical regions. The high level of aggregation can however blur important regional differences. Future versions of this inventory should therefore try to take into account more detailed data, e.g., on biomass loads.

[55] Our results suggest a significant increase in the emissions from wildfires throughout the period from 1960 to 2000 due to the increasing importance of forest and peat soil burning. Annual global carbon emissions averaged at 1660 Tg C/a during the 1960s and rose to an average of 2560 Tg C/a during the 1990s. The most important contribution to the trend comes from enhanced deforestation in the tropical regions.

[56] In spite of the recent advances in the use of satellite data for estimating burned areas, considerable uncertainties remain in the quantification of this crucial quantity. Many of the uncertainties are related to the relatively coarse resolution of the satellite data products (typically 1×1 km^2). Many fires, in particular in the tropics, are of much smaller size, and they can therefore either remain undetected or their size can be determined wrongly. Potentially, this problem can be overcome by using finer resolution Landsat TM imagery, or with the help of new retrieval approaches analyzing fire radiative energy from the spectral signature [*Wooster et al.*, 2003, 2005; *Roberts et al.*, 2005]. However, none of these options can provide any information on burned areas before the satellite era, and the uncertainties will therefore remain very large for the time period before the late 1970s.

[57] The comparison between different literature studies on global or continental-scale wildland fire emissions revealed several large differences, which can sometimes be traced back to the use of different burned area products, the investigation of different time periods or the use of different emission factors. However, in many cases the reasons for discrepancies between the literature studies remain unclear, because different methodologies were employed and the results were reported in different ways [see also *Liousse et al.*, 2004]. It would be highly desirable if the community could define some common standards and perhaps establish a joint database for the auxiliary data used to estimate global wildland fire emissions. We believe that the apparent uncertainties of fire emissions in some regions are to some extent artificial, because some known biases of input data were not corrected for. Nevertheless, one must acknowledge the large uncertainties of several important quantities, particularly in relation to fire behavior (fraction of biomass consumed, ratio of flaming over smoldering combustion, etc.). A formal uncertainty analysis is difficult to undertake, because many of these parameters are correlated. On the basis of the detailed analysis of the literature (discussed mainly in the auxiliary material) and on the results from inverse modeling studies of CO [*Pétron et al.*, 2004; *Arellano et al.*, 2004], we estimate the uncertainties as follows: global direct carbon emissions for the 1980s and 1990s are probably reproduced within ±50% while global CO emissions for the same time period are uncertain by a factor of 2. The emissions of other species and of earlier time periods are even more uncertain and regional-scale estimates may be wrong by a factor of 5 or so occasionally.

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References

Achard, F., H. D. Eva, P. Mayaux, H.-J. Stibig, and A. Belward (2004), Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s, *Global Biogeochem. Cycles*, *18*, GB2008, doi:10.1029/2003GB002142.

Amiro, B. D., J. B. Todd, B. M. Wotton, K. A. Logan, M. D. Flannigan, B. J. Stocks, J. A. Mason, D. L. Martell, and K. G. Hirsch (2001), Direct carbon emissions from Canadian forest fires, 1959 to 1999, *Can. J. For. Res.*, *31*, 512–525.

Andreae, M. O. (1991), iomass burning: Its history, use, and distribution, and its impact on environmental quality and climate, in *Global Biomass Burning, Atmospheric, Climatic, and Biospheric Implications*, edited by J. S. Levine, pp. 3–21, MIT Press, Cambridge, Mass.

Andreae, M. O., and P. Merlet (2001), Emission of trace gases and aerosols from biomass burning, *Global Biogeochem. Cycles*, *15*(4), 955–966.

Arellano, A. F., Jr., P. S. Kasibhatla, L. Giglio, G. R. van der Werf, and J. T. Randerson (2004), Top-down estimates of global CO sources using MOPITT measurements, *Geophys. Res. Lett.*, *31*, L01104, doi:10.1029/2003GL018609.

Barbosa, P. M., D. Stroppiana, J.-M. Grégoire, and J. M. Cardoso Pereira (1999), An Assessment of Vegetation Fire in Africa (1981–1991):

Burned Areas, Burned Biomass, and Atmospheric Emissions, *Global Biogeochem. Cycles*, *13*, 933–950.

Bond, T. C., D. G. Streets, K. F. Yarber, S. M. Nelson, J.-H. Woo, and Z. Klimont (2004), A technology-based global inventory of black and organic carbon emissions from combustion, *J. Geophys. Res.*, *109*, D14203, doi:10.1029/2003JD003697.

Boschetti, L., H. D. Eva, P. A. Brivio, and J. M. Grégoire (2004), Lessons to be learned from the comparison of three satellite-derived biomass burning products, *Geophys. Res. Lett.*, *31*, L21501, doi:10.1029/2004GL021229.

Cahoon, D. R., B. J. Stocks, J. S. Levine, W. R. Cofer, and J. M. Pierson (1994), Satellite analysis of the severe 1987 forest fires in northern China and southeastern Siberia, *J. Geophys. Res.*, *99*, 18,627–18,638.

Chin, M., P. Ginoux, S. Kinne, O. Torres, B. N. Holben, B. N. Duncan, R. V. Martin, J. A. Logan, A. Higurashi, and T. Nakajima (2002), Tropospheric aerosol optical thickness from the GOCART model and comparisons with satellite and Sun photometer measurements, *J. Atmos. Sci.*, *59*, 461–483.

Christian, T. J., B. Kleiss, R. J. Yokelson, R. Holzinger, P. J. Crutzen, W. M. Hao, B. H. Saharjo, and D. E. Ward (2003), Comprehensive laboratory measurements of biomass-burning emissions: 1. Emissions from Indonesian, African, and other fuels, *J. Geophys. Res.*, *108*(D23), 4719, doi:10.1029/2003JD003704.

Cooke, W. F., and J. N. Wilson (1996), A global black carbon aerosol model, *J. Geophys. Res.*, *101*, 19,395–19,409.

DeFries, R., R. A. Houghton, M. C. Hansen, C. B. Field, D. Skole, and J. Townshend (2002), Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s, *Proc. Natl. Acad. Sci.*, *99*, 14,256–14,261.

Dentener, F., et al. (2006), Emissions of primary aerosol and precursor gases in the years 2000 and 1750 prescribed data-sets for AeroCom, *Atmos. Chem. Phys.*, *6*, 4321–4344.

Duncan, B. N., R. V. Martin, A. C. Staudt, R. Yevich, and J. A. Logan (2003), Interannual and seasonal variability of biomass burning emissions constrained by satellite observations, *J. Geophys. Res.*, *108*(D2), 4100, doi:10.1029/2002JD002378.

Food and Agriculture Organisation (FAO) (2003), WRB map of world soil resources, Land and Water Dev. Div. AGL, Rome. (Available at http://www.fao.org/ag/agl/agll/wrb/soilres.htm)

Food and Agriculture Organisation (FAO) (2005), Global forest resources assessment: Progress towards sustainable forest management, United Nations, Rome.

Finney, M. A. (1998), FARSITE: Fire area simulator-model development and evaluation, *Res. Pap. RMRS-RP-4*, 47 pp., U.S. Dep. of Agric., For. Serv., Rocky Mt. Res. Stn., Ogden, Utah.

French, N. H. F., E. S. Kasischke, and D. G. Williams (2002), Variability in the emission of carbon-based trace gases from wildfire in the Alaskan boreal forest, *J. Geophys. Res.*, *107*, 8151, doi:10.1029/2001JD000480, [printed *108*(D1), 2003].

Friedl, M. A., et al. (2002), Global landcover mapping from MODIS: algorithms and early results, *Int. J. Remote Sens.*, *83*, 287–302.

Galanter, M., H. Levy II, and G. R. Carmichael (2000), Impacts of biomass burning on tropospheric CO, NO_x, and O_3, *J. Geophys. Res.*, *105*, 6633–6653.

Generoso, S., F.-M. Bréon, Y. Balkanski, O. Boucher, and M. Schulz (2003), Improving the seasonal cycle and interannual variations of biomass burning aerosol sources, *Atmos. Chem. Phys.*, *3*, 1211–1222.

Giglio, L., and J. D. Kendall (2004), Commentary on "Improving the seasonal cycle and interannual variations of biomass burning aerosol sources" by Generoso et al., *Atmos. Chem. Phys.*, *4*, 585–587.

Goldammer, J., A. Sukhinin, and I. Csiszar (2003), The current fire situation in the Russian Federation: Implications for enhancing international and regional cooperation in the UN Framework and the Global Programs on Fire Monitoring and Assessment, GFMC contribution to the International Workshop "New Approaches to Forest Protection and Fire Management at an Ecosystem Level", Khabarovsk, Russian Federation, 9–12 Sept. (Available at http://www.gfmc.org)

Goldewijk, K. K. (2005), Three centuries of global population growth: A spatial referenced population density database for 1700–2000, *Popul. Environ.*, *26*(4), 343–367.

Hao, W. M., and M. H. Liu (1994), Spatial and temporal distribution of tropical biomass burning, *Global Biogeochem. Cycles*, *8*, 495–503.

Hao, W. M., M. H. Liu, and P. J. Crutzen (1990), Estimates of annual and regional releases of CO_2 and other trace gases to the atmosphere from fires in the tropics, based on the FAO statistics for 1975–1980, in *Fire in the Tropical Biota*, *Ecol. Stud.*, vol. 84, edited by J. G. Goldammer, pp. 440–462, Springer, New York.

Heald, C. L., D. J. Jacob, D. B. A. Jones, P. I. Palmer, J. A. Logan, D. G. Streets, G. W. Sachse, J. C. Gille, R. N. Hoffman, and T. Nehrkorn (2004), Comparative inverse analysis of satellite (MOPITT) and aircraft (TRACE-P) observations to estimate Asian sources of carbon monoxide, *J. Geophys. Res.*, *109*, D23306, doi:10.1029/2004JD005185.

Heil, A., B. Langmann, and E. Aldrian (2006), Indonesian peat and vegetation fire emissions: Study on factors influencing large-scale smoke haze pollution using a regional atmospheric chemistry model, *Mitigation Adaptation Strategies Global Change*, *12*, 113–133, doi:10.1007/s11027-006-9045-6.

Hély, C., K. Caylor, S. Alleaume, R. J. Swap, and H. H. Shugart (2003), Release of gaseous and particulate carbonaceous compounds from biomass burning during the SAFARI 2000 dry season field campaign, *J. Geophys. Res.*, *108*(D13), 8470, doi:10.1029/2002JD002482.

Hoelzemann, J. J. (2006), Global wildland fire emission modeling for atmospheric chemistry studies, Ph.D. thesis, Int. Max Planck Res. Sch. on Earth Syst. Modell., Hamburg, Germany.

Hoelzemann, J. J., M. G. Schultz, G. P. Brasseur, C. Granier, and M. Simon (2004), Global Wildland Fire Emission Model (GWEM): Evaluating the use of global area burnt satellite data, *J. Geophys. Res.*, *109*, D14S04, doi:10.1029/2003JD003666.

Houghton, R. A. (2003), Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000, *Tellus, Ser. B*, *55*, 378–390.

Houghton, R. A. (2005), Aboveground forest biomass and the global carbon balance, *Global Change Biol.*, *11*, 945–958, doi:10.1111/j.1365-2486.2005.00955.x.

Hurst, D. F., D. W. T. Griffith, and G. D. Cook (1994), Trace gas emissions from biomass burning in tropical Australian savannas, *J. Geophys. Res.*, *99*, 16,441–16,456.

Ichoku, C., and Y. Kaufman (2005), A method to derive smoke emission rates from MODIS fire radiative energy measurements, *IEEE Trans. Geosci. Remote Sens.*, *43*, 2636–2649.

Intergovernmental Panel on Climate Change (2001), *Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., 881 pp., Cambridge Univ. Press, New York.

Ito, A., and J. E. Penner (2004), Global estimates of biomass burning emissions based on satellite imagery for the year 2000, *J. Geophys. Res.*, *109*, D14S05, doi:10.1029/2003JD004423.

Ito, A., and J. E. Penner (2005a), Estimates of CO emissions from open biomass burning in southern Africa for the year 2000, *J. Geophys. Res.*, *110*, D19306, doi:10.1029/2004JD005347.

Ito, A., and J. E. Penner (2005b), Historical emissions of carbonaceous aerosols from biomass and fossil fuel burning for the period 1870–2000, *Global Biogeochem. Cycles*, *19*, GB2028, doi:10.1029/2004GB002374.

Ito, A., A. Ito, and H. Akimoto (2007), Seasonal and interannual variations in CO and BC emissions from open biomass burning in Southern Africa during 1998–2005, *Global Biogeochem. Cycles*, *21*, GB2011, doi:10.1029/2006GB002848.

Kasischke, E. S., and M. R. Turetsky (2006), Recent changes in the fire regime across the North American boreal region-Spatial and temporal patterns of burning across Canada and Alaska, *Geophys. Res. Lett.*, *33*, L09703, doi:10.1029/2006GL025677.

Kasischke, E. S., J. H. Hewson, B. Stocks, G. van der Werf, and J. Randerson (2003), The use of ATSR active fire counts for estimating relative patterns of biomass burning: A study from the boreal forest region, *Geophys. Res. Lett.*, *30*(18), 1969, doi:10.1029/2003GL017859.

Kasischke, E. S., E. J. Hyer, P. C. Novelli, L. P. Bruhwiler, N. H. F. French, A. I. Sukhinin, J. H. Hewson, and B. J. Stocks (2005), Influences of boreal fire emissions on Northern hemisphere atmospheric carbon and carbon monoxide, *Global Biogeochem. Cycles*, *19*, GB1012, doi:10.1029/2004GB002300.

Lavoué, D., C. Liousse, H. Cachier, B. J. Stocks, and J. G. Goldammer (2000), Modeling of carbonaceous particles emitted by boreal and temperate wildfires at northern latitudes, *J. Geophys. Res.*, *105*, 26,871–26,890.

Liousse, C., J. E. Penner, C. Chuang, J. J. Walton, H. Eddleman, and H. Cachier (1996), A global three-dimensional model study of carbonaceous aerosols, *J. Geophys. Res.*, *101*, 19,411–19,432.

Liousse, C., et al. (2004), Deriving global quantitative estimates for spatial and temporal distributions of biomass burning emissions, in *Emissions of Atmospheric Trace Compounds*, edited by C. Granier et al., pp. 71–113, Kluwer Acad., Dordrecht, Netherlands.

Lobert, J. M., W. C. Keene, J. A. Logan, and R. Yevich (1999), Global chlorine emissions from biomass burning: Reactive chlorine emissions inventory, *J. Geophys. Res.*, *104*, 8373–8389.

Mota, B. W., J. M. C. Pereira, D. Oom, M. J. P. Vasconcelos, and M. Schultz (2006), Screening the ESA ATSR-2 World Fire Atlas (1997–2002), *Atmos. Chem. Phys.*, *6*, 1409–1424.

Mouillot, F., and C. B. Field (2005), Fire history and the global carbon budget: a 1° ×1° fire history reconstruction for the 20th century, *Global Change Biol.*, *11*, 398–420, doi:10.1111/j.1365-2486.2005.00920.x.

Osborne, P. (2000), *Tropical Ecosystems and Ecological Concepts*, Cambridge Univ. Press, Cambridge, UK.

Page, S. E., F. Siegert, J. O. Rieley, H. D. V. Boehm, A. Jaya, and S. Limin (2002), The amount of carbon released from peat and forest fires in Indonesia during 1997, *Nature*, *420*(6911), 61–65.

Pereira, J. M. C. (2003), Remote sensing of burned areas in tropical savannas, *Int. J. Wildland Fire*, *12*, 259–270.

Pétron, G., C. Granier, B. Khattatov, V. Yudin, J.-F. Lamarque, L. Emmons, J. Gille, and D. P. Edwards (2004), Monthly CO surface sources inventory based on the 2000–2001 MOPITT satellite data, *Geophys. Res. Lett.*, *31*, L21107, doi:10.1029/2004GL020560.

Potter, C., V. Brooks-Genovese, S. Klooster, and A. Torregrosa (2002), Biomass burning emissions of reactive gases estimated from satellite data analysis and ecosystem modeling for the Brazilian Amazon region, *J. Geophys. Res.*, *107*(D20), 8056, doi:10.1029/2000JD000250.

Prins, E. M., W. P. Menzel, and D. E. Ward (1996), GOES-8 ABBA diurnal fire monitoring during SCAR-B, in *Smoke/Sulfate, Clouds and Radiation—Brazil (SCAR-B) Proceedings*, pp. 153–157, Transtec Editorial, Fortaleza, Brazil, 4–8 Nov.

Prins, E. M., J. M. Feltz, W. P. Menzel, and D. E. Ward (1998), An overview of GOES-8 diurnal fire and smoke results for SCAR-B and 1995 fire season in South America, *J. Geophys. Res.*, *103*, 31,821–31,835.

Pulles, T., M. van het Bolscher, R. Brand, and A. Visschedijk (2007), Assessment of global emissions from fuel combustion in the final decades of the 20th Century, *TNO Rep. 2007-A-R0132B*, Ned. Org. voor toegepast Natuurwet. Onderzoek, Apeldoorn, Netherlands.

Pyne, S., P. Andrews, and R. Laven (1996), *Introduction to Wildland Fire*, John Wiley, New York.

Ramankutty, N., and J. A. Foley (1999), Estimating historical changes in global land cover: Croplands from 1700 to 1992, *Global Biogeochem. Cycles*, *13*(4), 997–1027.

Reid, J. S., R. Koppmann, T. F. Eck, and D. P. Eleuterio (2005), A review of biomass burning emissions. part II: Intensive physical properties of biomass burning emissions, *Atmos. Chem. Phys.*, *5*, 799–825.

Roberts, G., M. J. Wooster, G. L. W. Perry, N. Drake, L.-M. Rebelo, and F. Dipotso (2005), Retrieval of biomass combustion rates and totals from fire radiative power observations: Application to southern Africa using geostationary SEVIRI imagery, *J. Geophys. Res.*, *110*, D21111, doi:10.1029/2005JD006018.

Robinson, J. M. (1989), On uncertainty in the computation of global emissions from biomass burning, *Clim. Change*, *14*, 243–261.

Russell-Smith, J., A. C. Edwards, and G. D. Cook (2003), Reliability of biomass burning estimates from savanna fires: Biomass burning in northern Australia during the 1999 Biomass Burning and Lightning Experiment B field campaign, *J. Geophys. Res.*, *108*(D3), 8405, doi:10.1029/2001JD000787.

Schoenberg, F. P., R. Peng, and J. Woods (2003), On the distribution of wildfire sizes, *Environmetrics*, *14*(6), 583–592.

Scholes, R. J., and S. R. Archer (1997), Tree-grass interactions in savannas, *Annu. Rev. Ecol. Syst.*, *28*, 517–544.

Schultz, M. G. (2002), On the use of ATSR fire count data to estimate the seasonal and interannual variability of vegetation fire emissions, *Atmos. Chem. Phys.*, *2*, 387–395.

Schultz, M. G., et al. (2007), RETRO emission data sets and methodologies for estimating emissions, RETRO Project report, Max Planck Inst. for Meteorol., Hamburg, Germany.

Seiler, W., and P. J. Crutzen (1980), Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning, *Clim. Change*, *2*, 207–247.

Sitch, S., et al. (2003), Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Global Vegetation Model, *Global Change Biol.*, *9*, 161–185.

Soja, A. J., W. R. Cofer, H. H. Shugart, A. I. Sukhinin, P. W. Stackhouse Jr., D. J. McRae, and S. G. Conard (2004), Estimating fire emissions and disparities in boreal Siberia (1998–2002), *J. Geophys. Res.*, *109*, D14S06, doi:10.1029/2004JD004570.

Stocks, B. J., et al. (2002), Large forest fires in Canada, 1959–1997, *J. Geophys. Res.*, *107*, 8149, doi:10.1029/2001JD000484, [printed *108*(D1), 2003].

Sukhinin, A. I., et al. (2004), AVHRR-based mapping of fires in Russia: New products for fire management and carbon cycle studies, *Remote Sens. Environ.*, *93*, 546–564.

Tansey, K., et al. (2004), Vegetation burning in the year 2000: Global burned area estimates from SPOT VEGETATION data, *J. Geophys. Res.*, *109*, D14S03, doi:10.1029/2003JD003598.

Thonicke, K., S. Venevsky, S. Sitch, and W. Cramer (2001), The role of fire disturbance for global vegetation dynamics: Coupling fire into a Dynamic Global Vegetation Model, *Global Ecol. Biogeogr.*, *10*, 661–677.

van der Werf, G., J. T. Randerson, G. J. Collatz, and L. Giglio (2003), Carbon emissions from fires in tropical and subtropical ecosystems, *Global Change Biol.*, *9*, 547–562.

van der Werf, G., J. T. Randerson, G. J. Collatz, L. Giglio, P. S. Kasibhatla, A. F. Arellano, S. C. Olsen, and E. S. Kasischke (2004), Continental-scale partitioning of fire emissions during the 1997 to 2001 El Niño/La Niña period, *Science*, *303*, 73–76.

van der Werf, G., J. T. Randerson, L. Giglio, G. J. Collatz, P. S. Kasibhatla, and A. F. Arellano Jr. (2006), Interannual variability in global biomass burning emissions from 1997 to 2004, *Atmos. Chem. Phys.*, *6*, 3423–3441.

Venevsky, S., K. Thonicke, S. Sitch, and W. Cramer (2002), Simulating fire regimes in human-dominated ecosystems: Iberian Peninsula case study, *Global Change Biol.y*, *8*, 984–998.

Ward, D. E., R. A. Susott, J. B. Kauffman, R. E. Babbitt, D. L. Cummings, B. Dias, B. N. Holben, Y. J. Kaufman, R. A. Rasmussen, and A. W. Setzer (1992), Smoke and fire characteristics for Cerrado and deforestation burns in Brazil: BASE-B experiment, *J. Geophys. Res.*, *97*, 14,601–14,619.

Ward, D. E., W. M. Hao, R. A. Susott, R. E. Babbitt, R. W. Shea, J. B. Kauffman, and C. O. Justice (1996), Effect of fuel composition on combustion efficiency and emission factors for African savanna ecosystems, *J. Geophys. Res.*, *101*, 23,569–23,576.

Williams, D. W., and A. M. Liebhold (1995), Herbivorous insects and global change: Potential changes in spatial distribution of forest defoliator outbreaks, *J. Biogeogr.*, *22*, 2229–2235.

Wooster, M., B. Zhukov, and D. Oertel (2003), Fire radiative energy for quantitative study of biomass burning: Derivation from the BIRD experimental satellite and comparison to MODIS fire products, *Remote Sens. Environ.*, *86*, 83–107.

Wooster, M. J., G. Roberts, G. L. W. Perry, and Y. J. Kaufman (2005), Retrieval of biomass combustion rates and totals from fire radiative power observations: FRP derivation and calibration relationships between biomass consumption and fire radiative energy release, *J. Geophys. Res.*, *110*, D24311, doi:10.1029/2005JD006318.

Wotawa, G., P. C. Novelli, M. Trainer, and C. Granier (2001), Inter-annual variability of summertime CO concentrations in the Northern Hemisphere explained by fires in North America and Russia, *Geophys. Res. Lett.*, *28*, 4575–4578.

Yevich, R., and J. A. Logan (2003), An assessment of biofuel use and burning of agricultural waste in the developing world, *Global Biogeochem. Cycles*, *17*(4), 1095, doi:10.1029/2002GB001952.

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