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ScienceDirect
Atmospheric Environment 41 (2007) 6931–6940
ATMOSPHERIC ENVIRONMENT
www.elsevier.com/locate/atmosenv

Global estimation of CO emissions using three sets of satellite data for burned area

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Received 31 May 2006; received in revised form 7 October 2006; accepted 8 October 2006

Abstract

Using three sets of satellite data for burned areas together with the tree cover imagery and a biogeochemical component of the Integrated Science Assessment Model (ISAM) the global emissions of CO and associated uncertainties are estimated for the year 2000. The available fuel load (AFL) is calculated using the ISAM biogeochemical model, which accounts for the aboveground and surface fuel removed by land clearing for croplands and pasturelands, as well as the influence on fuel load of various ecosystem processes (such as stomatal conductance, evapotranspiration, plant photosynthesis and respiration, litter production, and soil organic carbon decomposition) and important feedback mechanisms (such as climate and fertilization feedback mechanism). The ISAM estimated global total AFL in the year 2000 was about 687 Pg AFL. All forest ecosystems account for about 90% of the global total AFL. The estimated global CO emissions based on three global burned area satellite data sets (GLOBSCAR, GBA, and Global Fire Emissions Database version 2 (GFEDv2)) for the year 2000 ranges between 320 and 390 Tg CO. Emissions from open fires are highest in tropical Africa, primarily due to forest cutting and burning. The estimated overall uncertainty in global CO emission is about $\pm$65%, with the highest uncertainty occurring in North Africa and Middle East region ($\pm$99%). The results of this study suggest that the uncertainties in the calculated emissions stem primarily from the area burned data.

Keywords: Open fire; CO; Inventory; ISAM

1. Introduction

Open biomass burning contributes substantially to changes in biogeochemical processes at both local and global level and produces emissions for trace gases and aerosols, which may ultimately alter global climate processes (Shea et al., 1996; Seiler and Crutzen, 1980). In particular, open biomass burning is an important source of ozone and methane precursors, such as CO, NMHCs, and NO_x (Andreae and Merlet, 2001), and contributes to high uncertainties in the estimates of pollutions in global chemistry transport models (Ito and Penner, 2006). Over the past 25 years, modeling and measurement efforts have been made to develop the trace gas and aerosol emission inventories from biomass burning at the global scale. Earlier global modeling studies made use of scattered and incomplete data information for available fuel load (AFL), combustion completeness (CC) or fraction of biomass consumed during fires, and emission

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1352-2310/$ - see front matter © 2006 Published by Elsevier Ltd.
doi:10.1016/j.atmosenv.2006.10.021

factors (EFs) (Crutzen and Andreae, 1990; Hao et al., 1990; Hao and Liu, 1994; Lobert et al., 1999; Galanter et al., 2000). While the earlier data information is sufficient to estimate the emission inventories for some regions, these data information are insufficient for estimating the emission inventories at the global scale. Because of these data limitations, more recent modeling studies have taken the advantage of available satellite remote-sensing data and/or more comprehensive biogeochemical models to estimate the amount of biomass burned and associated emissions (van der Werf et al., 2003, 2004; Ito and Penner, 2004; Hoelzemann et al., 2004; Jain et al., 2006). However, most of the modeling studies have highlighted the fact that even though the satellite data products provide information on the spatial and temporal scale, considerable uncertainty exists in the estimated emission inventories (Ito and Penner, 2006; Kasischke and Penner, 2004; French et al., 2004).

Building on our previous work (Jain et al., 2006) where we implemented algorithms for open fire biomass burning into our terrestrial ecosystem model (Jain and Yang, 2005), the objective of this study is to quantify uncertainties in the model estimated global and regional emissions of CO from open fires using the error propagation analysis method.

Since the global burnt area is one of the most important but uncertain factors in developing more refined emission estimates from open fires, this study uses three recently available satellite data sets for the global area burnt.

2. Methodology

The emission calculations associated with open fires were carried out using the *standard method* for estimating emissions from biomass burning (Seiler and Crutzen, 1980; Hao et al., 1990; Pereira et al., 1999; Potter et al., 2002). According to *standard method*, the total emissions (E, Tg yr^{-1}) of a gas are the product of four parameters: burnt area (km^2), A; available fuel load or burnable plant material, AFL (kg dry matter km^{-2}), combustion completeness or efficiency for vegetation type, CC; and emission factor of a gas for an open fire, EF (g species kg dry matter^{-1}). Estimates of these four parameters are described in detail in the work of Jain et al. (2006); a brief account of these parameters and the uncertainties in these parameters are provided here.

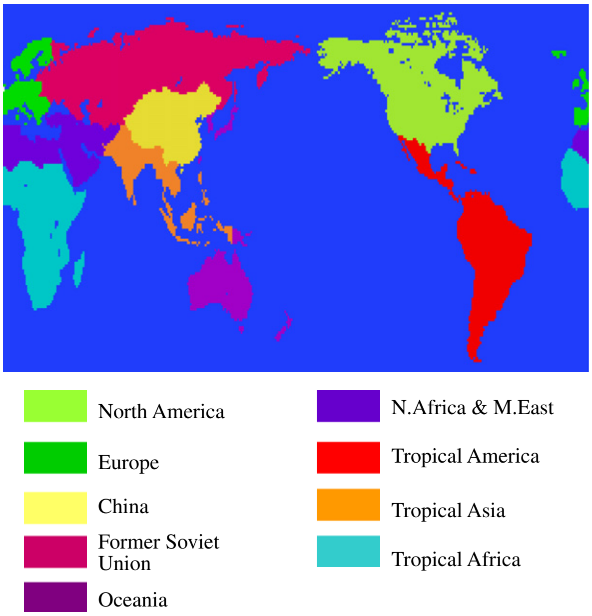

Fig. 1. Geographical distributions of the nine regions considered in this study for the regional biomass-burning emission analysis.

The CO emissions are calculated at $0.5^\circ \times 0.5^\circ$ spatial resolution. The regional analysis of CO emissions is done for nine regions, which are depicted in Fig. 1.

2.1. Burnt area

For the global burnt area we have used three of the latest open fire products recently made available to estimate the CO emission. All three of the products are compilations of global monthly area burned from three different remote-sensing satellites. The two data sets, GLOBSCAR (Simon et al., 2004) and GBA (Grégoire et al., 2003; Tansey et al., 2004), are for the year 2000 and provide the monthly areas burned globally at 1 km × 1 km resolution. GLOBSCAR data are based on the ESA ERS-2 satellite data (Simon et al., 2004). The GBA data set is based on SPOT-VGT-S1 satellite (Grégoire et al., 2003; Tansey et al., 2004). The third data set, Global Fire Emissions Database version 2 (GFEDv2) (van der Werf et al., 2006), provides monthly global area burned for the years 1997–2001 at $1^\circ \times 1^\circ$ deg resolution. The GFEDv2 data were originally derived from Tropical Rainfall Measuring (TRMM) Visible and Infrared Scanner satellite data (van der Werf et al., 2003), which has recently been modified based on active fires and burned area derived during the later MODIS period (2001–2004) (Giglio et al., 2005).

The annual global burned areas used in this study for the year 2000 based on GLOBSCAR, GBA and GFEDv2 data sets were about 1.92, 3.56, and 3.51 million km^2. Overall the GBA and GFEDv2 results for most regions are in good agreement, but GLOBOSCAR results for most of the regions are substantially different from both the GBA and GFEDv2 results (Fig. 2). Except for North America, the annual burnt area recorded by GLOBSCAR in all regions is lower than one of the two data sets. The most notable regional differences between GLOBOSCAR and other two data sets are seen in tropical Africa, tropical Asia, and Oceania. The GLOBSCAR results for area burnt in these regions are about 50% or more lower than the results of other two data sets, perhaps due to the inability of GLOBSCAR algorithms to detect large areas of woodland and shrub land burning (Simon et al., 2004). In Europe, North Africa, and the Middle East burnt area based on all three data sets are approximately the same. In case of Former Soviet Union, both the GLOBSCAR figures and GBA results are larger GFEDv2-based results.

2.2. Available fuel load

In this study the global biomass density to determine AFL or pre-burnable plant material is calculated using the terrestrial component of our Integrated Science Assessment Model (ISAM) (Jain and Yang, 2005). The purpose of the model used in this study is to represent the current state-of-the-art knowledge of terrestrial ecosystems while at the same time studying the effects of human-induced land-use emissions on terrestrial ecosystems and biomass density. For this study the model simulates the carbon fluxes to and from different compartments of the terrestrial biosphere with $0.5^\circ \times 0.5^\circ$ spatial resolution. Each grid cell is completely occupied by at least one of the 12 natural land-coverage classifications and/or croplands according to the vegetation maps of Loveland and Belward (1997) and Haxeltine and Prentice (1996), and by at least one of the 105 soil types based on the FAO-UNESCO Soil Map of the World (Zobler, 1986, 1999). In this study we have considered only 10 natural vegetation types and croplands. Within each grid cell, the carbon dynamics of each land-coverage classification are described by an ecosystem model consisting of ground vegetation (GV) representing herbaceous carbon reservoirs; non-woody tree part (NWT) representing foliage, flowers, and roots in transition; and woody tree parts (WT) representing branches, boles, and most root material of trees; two litter reservoirs (decomposable plant material (DPM) and resistant plant material (RPM)),

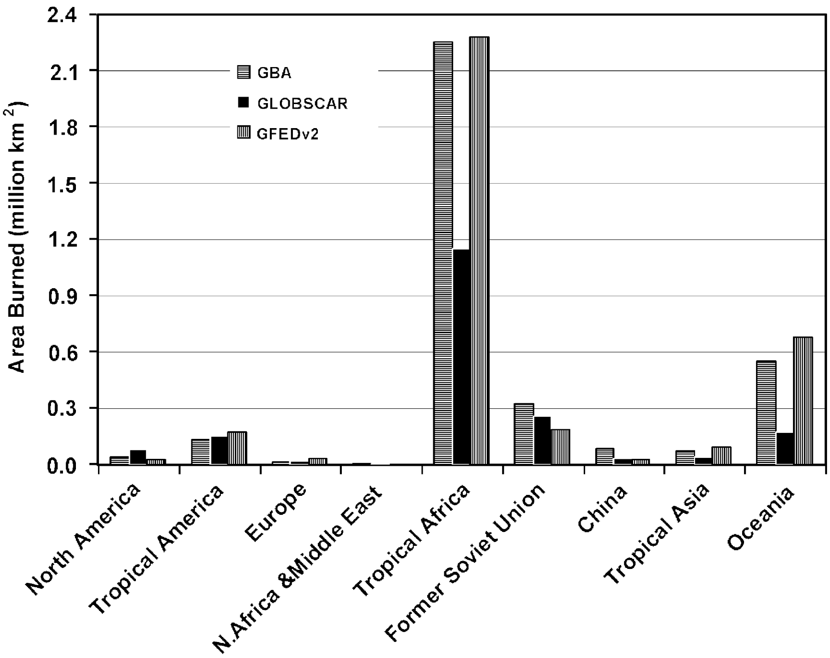

Fig. 2. Regional area burned (million km^2) from the open fires in the year 2000 based on GLOBSCAR, GBA, and GFEDv2 data sets.

representing litter input from above- and below-ground litter biomass plant parts; and three soil reservoirs (microbial biomass, humified organic matter, and inert organic matter).

There are many features of this model that make it more suitable for estimating fuel loads. First, the separation between GV and two tree parts (NWT and WT) along with satellite-derived tree density data (Zhu and Waller, 2003), which allow us to account for the distinct woody and non-woody biomass variation within each ecosystem type. Second, this model makes a distinction between two kinetically defined pools of plant litter: metabolic or DPM and structural or RPM. The metabolic component (DPM) constitutes the cytoplasic compounds of plant cell and is more susceptible for the fires, whereas the structural pool (RPM) represents cell wall with bound protein and lignified structure and less susceptible for the fires as compared to DPM. This unique feature allows us to properly account for partially decomposed organic material fuel in the upper portion of ground surface vegetation.

In order to calculate AFL for the year 2000, we first initialize the vegetation model with a 1765 atmospheric CO_2 concentration of 278 ppmv to calculate the equilibrium NPP in addition to vegetation and soil carbon for different model pools. Next, the model is run up to the year 2000 using prescribed observed temperature and precipitation changes (Mitchell et al., 2004) and CO_2 concentrations (Neftel et al., 1985; Friedli et al., 1986; Keeling and Whorf, 2000). We also utilized surveys of past land cover changes due to three types of land cover change activities: clearing of natural ecosystems for croplands and/or pasturelands, recovery of abundant croplands/pasturelands to pre-conversion natural vegetation, and production and harvest in conversion areas (Jain and Yang, 2005).

Figs. 3a and b show our ISAM estimated global AFL density ($g\,m^{-3}$) for forests and non-forests ecosystem types for the year 2000. The ISAM estimated global total AFL density for forest and non-forests biomes are 14,259 and 1073 $g\,m^{-2}$. The forest and non-forest biomes account for 90% and 10% of the global total AFL (687 Pg AFL yr^{-1}). It is important to recognize that there is no consistent global map of AFL available in the open literature. Most of the field experiment studies available in the literature have been carried out on a very specific region or a country using diverse methods. Therefore, the uncertainties in the available literature values are generally quite large. The uncertainties in our estimated AFL values are discussed in Section 3.

2.3. Combustion completeness and emission factors

CC or the combustion fraction is highly variable between different fires under different conditions even in similar vegetation types. In this study, ecosystem types with similar characteristics are grouped together and assigned a CC (Jain et al., 2006). Later we calculated the uncertainties in the results associated with the uncertainties in the CC values. And the uncertainties assumed in CC values are much larger than the uncertainties determined based on the range of values. EFs are estimations of the mass of a given species emission relative to some measurement of total burnt material. In this study, all EFs are given in terms of g species kg dry matter^{-1}. This study uses regional natural vegetation-based EFs as presented in Jain et al. (2006), which are compiled from several publications for various regions and ecosystems.

3. Uncertainty analysis

There are undoubtedly errors in the modeling method used here to estimate biomass-burning emissions due to uncertainties associated with the various input variables used. Previous biomass-burning modeling studies have used different error analysis methods to evaluate the errors associated with their model results. For example, Scholes et al. (1996) used "classification method" to estimate the biomass burned annually in vegetation fires in Africa. This method is based on the multiple correlation coefficient values for the empirical relationships on which the model is based. More recently, French et al. (2004) carried out uncertainty analysis using a Monte Carlo approach to calculate the uncertainties in carbon emission for fire from Boreal regions of Alaska. Although Monte Carlo approach is a rigorous uncertainty analysis approach and is useful if statistical properties of the input data and equations used are available. Here we use a more conservative uncertainty analysis approach, i.e., error propagation analysis, to evaluate the overall uncertainty in our emission estimates:

$$\Delta E = \sqrt{\left(\sum_{i=1}^{N} \frac{\partial F}{\partial x_i} \Delta x_i\right)^2},$$

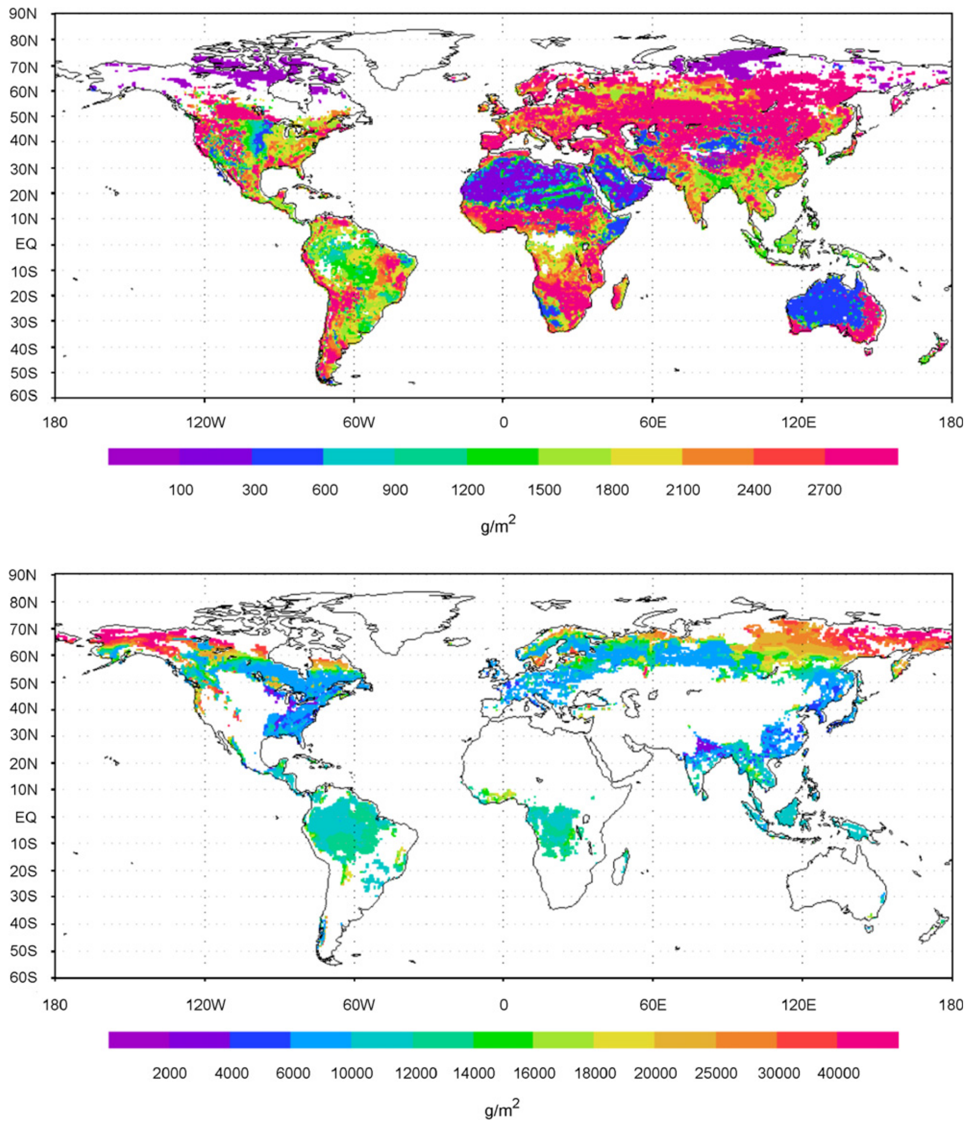

Fig. 3. ISAM estimated available fuel load (AFL in $g\,m^{-2}$) for the year 2000. The top panel shows the AFL for all non-forests ecosystems and bottom panel shows the AFL for all forests ecosystems.

where ΔE is the absolute error (overall uncertainty) of the derived quantity; N is the number of factors x_i with uncertainty Δx_i; and $\partial F/\partial x_i$ is the partial derivative of the function F with respect to each x_i. The uncertainty results are reported here in the form of % relative uncertainty defined as $(\Delta E/E) \times 100\%$, where E is total CO emissions.

We applied the error propagation analysis to four parameters of biomass-burning equation discussed in Section 2: area burned (A), AFL, CC, and EFs.

The area burned used in this study is based on three different satellite data sets that each provides a range of values for each region. We define uncertainties in the area burnt for different regions relative to the mean of the maximum and the minimum range of values given in Fig. 2. Relative uncertainties in area burnt according to the data sets are as high as $\pm 69\%$ in the North America and Middle East region. Other regions with more than 25% uncertainties are Oceania (± 60), China (± 51), North America (± 48), Tropical Asia (± 42), Europe (± 41), Tropical Africa (± 33), and Former Soviet Union (± 27).

Uncertainty in AFL is determined based on the uncertainties in ISAM estimated biomass density. Presently, there is no objective way to define the uncertainty in model-estimated biomass density. In order to conduct our analysis, we assume a ±30% uncertainty for the model biomass (Scholes et al., 1996). For the uncertainty of EFs, we used Andreae and Merlet (2001) estimates given in Table 1. For each gas, these uncertainty levels are ecosystem specific. The error in burn completeness for all ecosystems is assumed to be about 25% as derived from the standard deviation of published results (Scholes et al., 1996).

4. Results

Our model estimated regional and global total CO emissions (in Tg CO yr^{-1}) and associated uncertainties for the year 2000 derived from GLOBSCAR, GBA, and GFEDv2 open fire data sets are given in Table 2. The model-estimated global total emissions based on GLOBSCAR are lower than the results based on the GBA and GFEDv2 data sets. This is mainly because the global total area burned for GLOBSCAR is substantially lower than from GBA and GFEDv2 data sets. Overall, our modeled lower (based on GLOBSCAR) and higher (based on GBA) range of global total emissions for 2000 are 320 406 Tg CO, whereas other modeling study estimates range between 171 and 429 Tg CO (Andreae and Merlet, 2001; Arellano et al., 2004; Duncan et al., 2003; Ito and Penner, 2004; van der Werf et al., 2003, 2004; Hoelzemann et al., 2004). In terms of regional CO emissions, Table 2 shows that there is no consistent pattern between three data set results. The CO emissions based on GLOBASCAR data are highest for North America and North Africa & Middle East regions, whereas the emissions are lowest for tropical Asia and Africa and Oceania regions. The GBA data set yields highest CO emissions for the Former Soviet Union and China and lowest emissions for Tropical America. In the case of GFEDv2 data set, the emissions are highest for Tropical America, Asia, and Africa, Europe and Oceania, and lowest for North America, Former Soviet Union, North America & Middle East, and China.

Fig. 4 illustrates the regional percentages of global total CO emissions for the year 2000 associated with the three open fire data sets. The percentage differences across different open fire burned data set results are 10% (in the case of North America) or less. The maximum percentage of CO emissions from open fires occurred in tropical Africa (46–55%), followed by the former Soviet Union (23–28%), North America (4–14%), tropical

Table 1
Uncertainties (±%) in emission factors for CO for different biomes (Andreae and Merlet, 2001)

Gas	Tropical evergreen	Tropical deciduous	Temperate evergreen	Temperate deciduous	Boreal	Savanna	Grassland/ pastureland	Shrubland	Cropland
CO	19	19	35	35	35	31	31	31	91

Table 2
ISAM estimated regional and global total CO emissions (in Tg CO yr^{-1}) and associated uncertainties (±%) for the year 2000 derived from GLOBSCAR, GBA, and GFEDv2 open fire data sets

	ISAM-GLOBSCAR		ISAM-GBA		ISAM-TRIM		Mean	
	Tg CO	%	Tg CO	%	Tg CO	%	Tg CO	%
Tropical America	19.3	±55	14.8	±57	32.9	±54	22.3	±55
Tropical Africa	146.1	±63	223.6	±63	237.2	±63	202.3	±63
Tropical Asia	9.1	±67	15.2	±68	22.3	±67	15.6	±67
North America	44.1	±75	17.6	±75	10.1	±75	23.9	±75
Europe	2.4	±78	2.9	±78	6.3	±74	3.9	±76
Former soviet union	90.8	±66	102.2	±67	61.1	±67	84.7	±67
North Africa and Middle East	1.1	±95	0.8	±100	0.05	±102	0.7	±99
China	3.8	±82	14.1	±79	3.3	±79	7.1	±80
Oceania	3.9	±84	15.4	±83	17.2	±82	12.2	±83
Global total	320.6	±66	406.7	±66	390.4	±64	372	±65

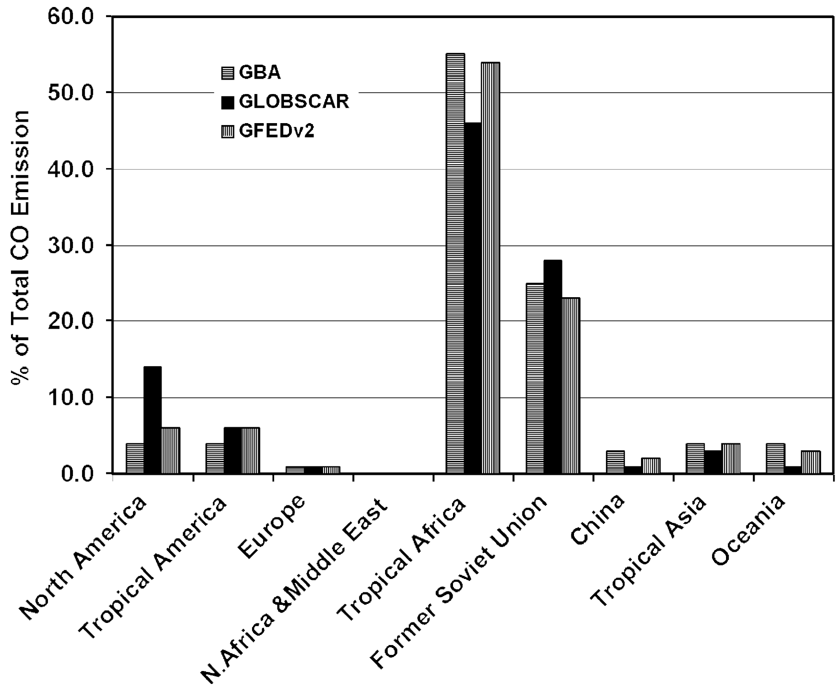

Fig. 4. Regional percentages (%) of global total CO emissions for the year 2000 associated with GLOBSCAR, GBA, and GFEDv2 open fire data sets.

America (4–6%), and Tropical Asia (3–4%). The contributions from other regions were 3% of the global total or less.

The estimated overall relative uncertainties in global total CO emissions associated with open fire for the year 2000 are about $\pm 65\%$. Consequently, the overall uncertainty range for the ISAM estimated global emissions associated with open fires is130–613 Tg CO. As for the uncertainties in the regional emissions, the estimated relative uncertainty is highest for North Africa and Middle East ($\pm 99\%$), then Oceanic ($\pm 83\%$), China ($\pm 80\%$), Europe ($\pm 76\%$), North America ($\pm 75\%$), Tropical Asia ($\pm 67\%$), Tropical Africa ($\pm 63\%$), and Tropical America ($\pm 55\%$).

5. Discussion and conclusions

Using three sets of satellite area burned data, the regional and global CO emissions and associated uncertainties are estimated for the year 2000. Our results suggest that the amount of biomass burned, and the resulting emissions at regional or global scales are strongly dependent on the global area burned data sets. While the three satellite burned products, GLOBSCAR, GBA, and GFEDv2, employed in this study provide a good starting point for our understanding of regional and global distributions of biomass burning and resultant emissions, the comparison of emission estimates based on three data products suggests that the uncertainty generated by these differences is high, particularly in North Africa and Middle East, Oceania, China, Europe and North America. There is a pressing need for greater accuracy of burnt area estimates.

The uncertainties in the amount of biomass burned as a result of open fires not only arise from the satellite burnt area measurement uncertainties, but also from the potentially burnable biomass density (or AFL) for many different ecosystem regions in the world, and CC. The estimates of AFL are mainly a function of aboveground carbon contents, which we estimated using our dynamic terrestrial ecosystem component of the ISAM. The incorporation of a 0.5° spatially resolved terrestrial model provides the essential capability for investigating potential changes in biomass-burning emissions due to changes in climate and land-use practice. In addition, we used forest inventory data to assess the quantity of forest resources. Nevertheless, uncertainties in our model results could be large, as there are not enough observations available at the global scale to validate the model results.

The uncertainty level is very difficult to quantify for CC because combustion processes are heterogeneous in nature and vary widely under different combustion conditions. There are studies that have shown statistically significant links between fuel moisture and CC especially in savanna ecosystems (Hoffa et al., 1999). Alternatively some studies are starting to base their CC estimates on fuel composition types as opposed to ecosystem types. For example, CCs are assigned to grasses/leaves, twigs, branches, and logs. The proportion of carbon that is stored in grasses/leaves, twigs, branches, or logs is then determined by ecosystem type, soil types, and weather factors. In the future this might be a more accurate way to assess CC for biomass-burning studies, especially if coupled with fuel moisture models.

Considerable progress has been made to determine accurate values of EF. In particular, Andreae and Merlet (2001) have critically evaluated the presently available data and integrated it into a consistent format. In this study, we assigned biome-specific EFs values based on Andreae and Merlet (2001). In spite of recent progress, gaps remain in the evaluation of EFs, particularly with respect to the estimates of biomass burned as a function of space, time, and type of combustion. For example, CO EFs are low during flaming combustion stage but significantly higher in the smoldering stage (Yokelson et al., 1997; Kasischke and Bruhwiler, 2003). Explicit representation of these two combustion stages would be desirable, but is not possible at this time because of limited data. The uncertainty associated with this parameterization and a host of other standard and necessary simplifications is difficult to assess.

It is worth mentioning here that the amount and accuracy of EF and CC data is not equally represented among ecosystems. Savanna and grasslands have received the majority of attention, and as such have some of the most refined data. Other ecosystems such as boreal forests are understudied and as such represent a large area of uncertainty. Future study of CCs and EFs in other ecosystems would be warranted to increase the accuracy of our current data.

In conclusion, given the high correlation between the emissions and area burnt, it is most likely that the uncertainties in the calculated biomass-burning emissions stem primarily from the area burned data for which we rely on the satellite measurements of burnt area. A second potential area of uncertainty is the AFL for which we rely on satellite-based land cover information and our terrestrial model. Similar conclusions have been made through review efforts of the Global Observations of Forest Cover project and the International Geosphere-Biosphere Program (Kasischke and Penner, 2004). Because of these issues, the full range of area monitoring at all scales, including integration of the ground-based observations with high-resolution satellite measurements may be in order. In conjunction with such efforts, local and global land cover changes could also be measured to validate the performance of terrestrial ecosystem models. In addition to observations, estimates of biomass density through prognosis of burning effects with more reliable and more complete terrestrial ecosystem models are also necessary. Moreover, in order to validate the model results, there is an urgent need for a network of ground and satellite-based long-term monitoring plans to measure changes in the land cover types at the local level. Such programs will be necessary to make reliable global emissions estimates from biomass burning.

Acknowledgements

I thank Xiaojuan Yang for her assistance with ISAM terrestrial model calculations and Zhining Tao for his assistance with the uncertainty calculations. This research was supported in part by the Office of Science (BER), US Department of Energy (DOE-DE-FG02-01ER63463).

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