Improving global estimates of atmospheric emissions from biomass burning

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[1] Biomass burning during wildland fires is an important source of atmospheric trace gasses and particulate matter. A meeting sponsored by Global Observation of Forest Cover/Global Observation of Land Dynamics and International Geosphere-Biosphere Program/International Global Atmospheric Chemistry/Biomass Burning Experiment to review the status of efforts using satellite-based burned-area products to estimate global emissions from biomass burning was held in July 2002. Here we summarize the results of papers submitted from this meeting and contained in this special section. In addition, the findings and recommendations from the workshop are summarized. While new burned-area products make it possible to estimate wildland fire emissions at continental and global scales, differences in approaches to quantify fuel loads and combustion factors lead to significant variations in emissions estimates. These differences highlight the need for in-depth comparisons between emission estimation approaches and further research directed toward integration of research conducted at regional scales into the global-scale approaches to estimate emissions. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 0325 Atmospheric Composition and Structure: Evolution of the atmosphere; 1610 Global Change: Atmosphere (0315, 0325); *KEYWORDS:* biomass burning, emissions, overview article

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1. Introduction

[2] The research of *Crutzen et al.* [1979] and *Seiler and Crutzen* [1980] first brought to light the role that biomass burning plays in determining the atmospheric concentration of a number of important atmospheric trace gases, as well as particulate matter. These initial studies provided the catalyst for extensive research over the past two decades to improve estimates of emissions from global biomass burning. Interdisciplinary studies have focused on four key areas (one global and three regional). At global scales, research has concentrated on developing estimates of burned area and seasonal patterns of active fire in regions where biomass burning occurs. At local, regional, and continental scales, research has emphasized quantifying the spatial and temporal variations in fuel loads and fuel moisture, estimating the combustion completeness or fraction of biomass consumed during fires as a function fuel type and moisture, and measuring emission factors for various trace gas species and particulate matter for different vegetation types and fuel moisture content.

[3] While information provided by fire management agencies in some regions is sufficient for determining the extent (burned area) and distribution of fires [see, e.g., *Kasischke et al.*, 2002; *Stocks et al.*, 2002], for most of the world, such data are insufficient for estimating emissions from biomass burning. Because of this data need, scientists began to evaluate the extent of biomass burning using satellite observations. International efforts to generate satellite fire products were initially coordinated through the International Geosphere-Biosphere Program's Data and Information System (IGBP-DIS) [*Justice and Dowty*, 1994; *Justice and Malingreau*, 1996]. The IGBP-DIS effort focused on a global product that was generated by processing 1-km-resolution thermal infrared data collected by the advanced very high resolution radiometer (AVHRR) satellite system [*Stroppiana et al.*, 2000].

[4] The coordinated effort started by the IGBP-DIS was continued through the Global Observation of Forest Cover (GOFC) project, which was initiated by the Committee on Earth Observation Satellites (CEOS) in 1997. Fire mapping and monitoring was identified as one of the three core elements for GOFC during its design phase. The GOFC project (now called the Global Observation of Forest Cover/Global Observation of Landcover Dynamics (GOFC/GOLD)) is part of the Global Terrestrial Observing System

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(GTOS). Workshops sponsored by GOFC/GOLD have focused on providing guidance in further refining requirements for satellite-based fire information products and on coordinating the efforts of different countries in the production, dissemination, and use of these products [*Ahern et al.*, 2001; *Justice et al.*, 2003]. These efforts are particularly important given the large number of new satellite systems deployed during the 1990s and early 2000s that have the potential for production of fire-related information products.

[5] The success of the IGBP-DIS in coordinating the generation of a global fire product on the basis of analyses of AVHRR data was a forerunner of efforts to create additional products based on the analyses of satellite thermal IR data, including the Along Track Scanning Radiometer (ATSR) (1997 to present; see *Arino et al.* [2001]), the Visible and Infrared Scanner (VIRS) (1998 to present; see *Giglio et al.* [2000]), and the Moderate-Resolution Imaging Spectrometer (MODIS) (2000 to present; see *Justice et al.* [2002]). Regional hot spot data products have also been generated from (AVHRR data for Canada (1999–2001; *Li et al.* [2000]) and eastern Russia (1995 to present; see *Soja et al.* [2004a]).

[6] One of the issues in using active fire information products derived from the analysis of thermal IR data to estimate burned area is that the algorithms are designed to only detect active fires, so they only represent a sample of total fire activity. Assuming that these data products represent an unbiased sample of total fire activity, *Dwyer et al.* [1998] used the IGBP-DIS product to analyze the spatial and temporal distribution of global fires, and *Dwyer et al.* [2000] used this product to analyze how fire distribution relates to vegetation and climate characteristics. *Schultz* [2002] and *Duncan et al.* [2003] used fire products from the ATSR satellite to analyze spatial and temporal variations in emissions from biomass burning.

[7] However, studies have shown that active fire products do not represent an unbiased sample of fire activity [*Eva and Lambin*, 1998; *Boles and Verbyla*, 2000; *Kasischke et al.*, 2003]. Recognizing this shortcoming, efforts were initiated to develop satellite fire products to quantify burned area. In addition, scientists also recognized that once reliable burned-area products became available, other factors would limit the accuracy of emissions estimates; in particular, issues associated with the determination of the spatial distribution of fuel loads and spatial/temporal variation of fuel moisture content and with the assessment of burn severity and combustion completeness. Recognizing these issues, the attendees of the GOFC/GOLD Fire Satellite Validation Workshop (held in Lisbon, Portugal, from 9 to 11 July 2001) recommended that a workshop focusing on Improving Global Estimates of Atmospheric Emissions from Biomass Burning be organized. Representatives from GOFC contacted scientists within IGBP's International Global Atmospheric Chemistry (IGAC) Biomass Burning Experiment (BIBEX) to organize a joint workshop, which was held on the campus of the University of Maryland in College Park from 10 to 12 July 2002. Specific objectives of the workshop were to:

[8] 1. Examine current methods and approaches for emissions modeling.

[9] 2. Present recent results from emissions models and determine the best estimates of biomass emissions, according to major biomes.

[10] 3. Identify current uncertainties and necessary improvements.

[11] 4. Refine the scientific requirements for observations and data products needed to reduce the uncertainties.

[12] 5. Recommend emissions products for a IGBP-IGAC-BIBEX-GOFC/GOLD sponsored model intercomparison to evaluate the scientific understanding of the effects of biomass emissions on the concentrations of trace gases and aerosols in the atmosphere.

[13] 6. Examine possible operational approaches for generation of input and output products for emissions models.

[14] This workshop was attended by over 70 participants and organized into a series of plenary sessions, poster sessions, and breakout discussions. The breakout sessions were organized to: (1) review the current status of procedures used to quantify and estimate emissions from biomass burning; (2) review the status of the inputs and data sets required to estimate emissions from biomass burning; and (3) make recommendations for the steps necessary to improve estimates of emissions from biomass burning. For each breakout session the participants were divided into three groups to discuss estimating emissions from wildland fires: (1) on a global basis; (2) in savannas/shrublands and tropical forests; and (3) in temperate and boreal forests. In this special section we present papers that were submitted for peer review several months after the completion of the workshop, as well as the major findings and recommendations from the workshop.

2. Summary of the Papers of the Special Section

[15] At the time of the GOFC/GOLD-IGBP workshop, work on two new global burned-area products was nearing completion. These new data sets were based on the analysis of burn scars and thus provided a basis for direct estimation of burned area. They are summarized in the papers by *Simon et al.* [2004] and *Tansey et al.* [2004]. Upon completion, these new burned-area products were used to estimate global emissions from wildland fires and are reported by *Hoelzemann et al.* [2004] and *Ito and Penner* [2004]. In addition, *Soja et al.* [2004b] estimated biomass burning emissions for eastern Russia for 1998–2002 using recently developed satellite-based burned-area estimates for this region. The studies of *Soja et al.* [2004b] and *Chuvieco et al.* [2004] highlight new approaches to address uncertainties in estimating emissions. In particular, Soja et al. report on the effects of varying the amounts of burning of organic soils in boreal regions on emissions estimates, while Chuvieco et al. report on the development of new techniques to estimate fuel moisture at the time of burning. Finally, the research by *French et al.* [2004] studied how uncertainties in the other parameters required to estimate biomass burning influence uncertainty, which is critical to developing priorities to further reduce errors in emissions estimates. In the following sections we summarize the key findings of the papers contained in this special section.

2.1. Global Burned-Area Products

[16] *Simon et al.* [2004] and *Tansey et al.* [2004] developed new estimates of burned area through mapping burn scars from satellite imagery. The advantages of burned-area mapping by satellite are that fires result in very distinct

Table 1. Comparison of Estimates of Burned Areas (in Millions of Hectares) Produced for 2000 by the GLOBSCAR and GBA-2000 Algorithms

	GLOBSCAR		GBA-2000		
	Total	Forest	Total	Forest	Shrubland/Woodland
Africa	121.0	20.6	224.6	2.7	23.9
North/Central America	11.0	3.3	6.2	0.9	3.8
South America	13.8	1.1	11.9	0.5	3.8
Australia	18.0		55.9	0.4	52.5
Asia	21.2	5.3	27.1	1.7	12.5
Europe	5.8	2.1	4.3	0.2	0.9
Russia	20.0	4.2	22.2	3.1	9.0
Global	210.7	36.6	352.2	9.6	106.5

alterations to vegetated surfaces that cause changes in the reflectance of solar radiation in the visible, near-infrared, and short-wave infrared regions of the electromagnetic spectrum, as well as changes in surface temperature. On the basis of these differences, algorithms can be implemented to discriminate between burned and unburned areas. The temporal frequency of imaging is an important factor in burn scar detection, as in certain regions, rapid postfire vegetation regrowth can impede burned-area detection. In other regions, burn scar signatures can persist for several years after a fire and may result in a false detection associated with a given year. To overcome sampling issues related to the rapid regrowth of vegetation requires using moderate resolution satellite systems with a high repeat frequency. For example, *Roy et al.* [1999, 2002] and *Korontzi et al.* [2003a] have shown that in subtropical regions, even though regrowth occurs within the same fire season, burn scars can be reasonably accurately quantified.

[17] *Simon et al.* [2004] present a burned-area product generated from data collected by the ATSR, and it is referred to as the GLOBSCAR product. *Tansey et al.* [2004] present a product generated from data collected by the SPOT-VEGETATION instrument, and it is referred to as the GBA-2000 product. It was agreed that both of these products would be generated using data collected during the year 2000 to facilitate comparisons. The GLOBSCAR product was based on data collected at a minimum of once every 3 days on the basis of the narrow swath of the ATSR sensor (509 km). SPOT-VEGETATION data had a daily repeat cycle because this instrument uses a wider swath. For analysis of burn scars in GBA-2000, a 10-day composite image was generated in order to address cloud cover issues that preclude sampling on a daily basis. Each product used satellite data with a nominal pixel size of 1 km.

[18] Different approaches were used to estimate burned area. The GLOBSCAR product used two algorithms that were applied to all data, while the GBA-2000 product was based on seven different sets of algorithms that were applied at regional scales. For 2000, the GLOBSCAR approach resulted in 211×10^6 ha of burned area globally, of which 37×10^6 ha were classified as forest. The GBA-2000 product resulted in 352×10^6 ha of burned area, of which only 10×10^6 ha were forest (Table 1). The GBA-2000 product reports substantially larger areas of burning in Africa and Australia, and *Simon et al.* [2004] attribute this difference to the inability of the GLOBSCAR algorithms to detect large areas of woodland and shrubland burning. Aside from these two regions, there appears to be general agreement between the two products at a continental scale (Table 1). The differences in forest area burned reported for the two products are difficult to interpret because each study used a different database to determine forest area; thus the differences in forest area burned in Table 1 may be due to variations in the vegetation base maps used, not the detection algorithms.

[19] *Simon et al.* [2004] present a more detailed comparison between the estimates of the GLOBSCAR data product and those from GBA-2000, as well as the fire hot spot product contained within the World Fire Atlas (WFA) generated from the analysis of thermal IR data collected by the ATSR instrument [see *Arino et al.*, 2001]. The data of *Simon et al.* [2004, Table 2] show that for the 20 countries with the highest fire activity, the GLOBSCAR 2000 product reported less area burned than the GBA-2000 product in 16 countries. For four countries (Brazil, Canada, Ukraine, and the United States), the GBA-2000 product reported substantially higher fire activity. *Simon et al.* [2004] report that the GBA-2000 over-reporting of burned area in Canada (based on comparison to fire management statistics) may be due to the mapping of older scars from fires during previous years. As expected, the burned-area estimates of the GLOBSCAR product are substantially higher than estimated using the WFA product. The ratio of WFA/GLOBSCAR area varies substantially between countries, supporting conclusions from earlier studies by *Kasischke et al.* [2003] that satellite-derived hot spot information cannot be used to assess relative fire activity between different regions, as has been attempted by some researchers [see, e.g., *Dwyer et al.*, 1998, 2000].

[20] The patterns of biomass burning at continental scales reported by the GLOBSCAR and GBA-2000 products are consistent with previous estimates of biomass burning activity, with Africa having the largest areas of fire. *van der Werf et al.* [2004] developed a global area burned from data collected by the VIRS instrument. The fire-hot spot product from VIRS was converted to area burned by developing a conversion factor for different biomes on the basis of estimating area burned from four scenes or tiles of MODIS satellite imagery. *van der Werf et al.* [2004] estimate there was 1040×10^6 ha burned in 2000 (G. van der Werf, personal communication, 2004), which is substantially higher than that estimated by GLOBSCAR and GBA-2000. In summary, the differences in area burned estimates highlight the need to carry out validation and intercomparison of different burned-area products.

2.2. Emission Estimates From Biomass Burning

[21] The different approaches being used to estimate biomass burning emissions using satellite data are high-

Table 2. Comparison of Estimates of Total Carbon Emissions From Global Biomass Burning Based on the Results From *Hoelzemann et al.* [2004] and *Ito and Penner* [2004]

	Area Burned, 10^6 ha	Carbon Emissions					
		Total, Tg	Emissions, t C ha^{-1}				
			Grasslands	Woodlands	Forests	Weighted
Ito and Penner [2004]						
North America	3.3	30.8	0.7	2.5	19.3	9.3
Central/South America	12.3	87.8	1.4	2.5	25.5	7.2
Europe, North Africa, west Russia, Middle East	13.4	37.5	0.9	3.1	18.4	2.8
Sub-Saharan Africa	217.3	931.5	1.4	2.9	23.6	4.3
Northeastern Asia	25.1	169.3	0.9	3.6	18.2	6.7
Southern Asia	8.6	62.8	2.0	5.8	26.8	7.3
Australia	33.9	108.5	1.5	3.0	23.3	3.2
Global	313.9	1428.0				4.6
Average			1.3	3.3	22.2	
Average fuel loads, t C ha^{-1}			1.9	6.8	60.6	
Hoelzemann et al. [2004]						
North America	7.0	196.1	4.3	16.7	29.2	27.9
Central America	2.0	43.7	1.8	6.6	27.6	21.3
South America	12.7	126.5	2.4	9.2	39.1	10.0
North Africa	60.4	408.7	1.4	7.6	34.6	6.8
South Africa	57.7	472.6	1.5	7.4	41.1	8.2
Western Europe	0.3	3.5	3.8	13.8	17.8	10.3
Eastern Europe	1.0	11.9	6.2	25.1	24.5	12.4
North central Asia	8.8	321.6	9.1	35.0	41.3	36.6
Near east Asia	0.8	5.4	2.6	8.7	23.3	6.6
Eastern Asia	0.0	0.1	2.3	12.2	22.1	9.2
Southern Asia	3.6	99.7	4.7	15.7	57.3	27.7
Oceania	17.8	51.6	1.0	3.8	30.0	2.9
Global	172.1	1741.0				10.1
Average			3.4	13.5	32.3	
Average fuel loads, t C ha^{-1}			4.0	22.5	64.6	

lighted in three papers presented in this special issue. *Ito and Penner* [2004] used the GBA-2000 data product supplemented by ATSR hot spot data provided from the World Fire Atlas as inputs into a global emissions model. To estimate the spatial distribution of biomass, Ito and Penner used satellite-derived maps of fractional tree cover derived from AHVRR data, combined with inventory-derived biomass estimates for some regions and approaches that empirically relate satellite vegetation indices to biomass in others. The location of below-ground fuels in the form of peats was estimated using a published global peatland map. Biomass was allocated into fuel available for burning on the basis of fractional vegetation cover and on estimates of tree-covered area. The combustion factors (fraction of available fuel consumed during a fire) were based on land-cover type (which was based on fractional tree cover). For forests the combustion factors were fixed for different fuel types (e.g., woody, herbaceous, and peat). For woodlands/shrublands the combustion factors varied as a function of fuel load. For grasslands it was assumed the combustion factors varied as a function of the amount of green leaf matter, which was estimated through analysis of a satellite-observed vegetation index on a monthly basis.

[22] *Hoelzemann et al.* [2004] used the GLOBSCAR burned-area product supplemented with data from the World Fire Atlas to produce estimates of emissions from global wildland fires. To estimate the global distribution of fuels, Hoelzemann et al. followed an approach first used by *van der Werf et al.* [2003], who estimated fuel loads using a satellite-based model that estimates net primary production. For this purpose, Hoelzemann et al. used the Lund-Potsdam-Jena (LPJ) Dynamic Global Vegetation Model to produce estimates of woody and herbaceous biomass and litter. These values were converted to available fuel on the basis of coefficients developed for different fuel types (litter, leaf, wood, and roots), vegetations types (grasslands, woodlands, and forests), and regions (tropical and temperate boreal). Combustion factors were varied by vegetation type and region.

[23] Table 2 summarizes the total carbon emissions generated by *Hoelzemann et al.* [2004] and *Ito and Penner* [2004]. Because the estimates of area burned are significantly different in each study (Table 1), the differences in total carbon emissions between the studies were expected. On a per unit area burned basis, however, the approach of *Hoelzemann et al.* [2004] produces twice the emissions as the approach of *Ito and Penner* [2004]. These higher emission rates are the result of a combination of higher fuel loads (Table 2) and combustion factors. The estimates of global biomass burning emissions of *Ito and Penner* [2004] (1428 Tg C) and *Hoelzemann et al.* [2004] (1741 Tg C) are both substantially lower than the 2600 Tg C emissions estimated by *van der Werf et al.* [2004]. These higher values are primarily due to variations in area burned, as the emission rate is lower in *van der Werf et al.* [2004] (2.5 t C ha^{-1} burned).

[24] A number of previous studies have focused on estimating emissions from fires in the boreal region [*Kasischke et al.*, 1995; *French et al.*, 2000, 2002; *Amiro et al.*, 2001; *Kajii et al.*, 2002; *Kasischke and Bruhwiler*, 2002]. These studies have highlighted a unique characteristic of burning in this region, specifically, the burning of organic

matter present in the deep organic mats present in the forests and peatlands of this region. *Soja et al.* [2004a, 2004b] build on previous efforts that emphasized the role of burning of ground-layer organic matter in boreal regions. They used a burned-area data set developed by Russian scientists through the processing of AVHRR data for the years 1998–2002. Aboveground fuels were estimated using forest inventory data sets that allocated total aboveground biomass into different fuel types (large woody material, branches and twigs, foliage, and litter). Combustion factors were derived based on fire type (surface versus crown) which, in turn, were inferred from the size of individual fire events. One of the more difficult parameters to estimate in boreal ecosystems is the amount of ground-layer organic matter (litter, moss, lichen, and organic soil) consumed during fires. *Amiro et al.* [2001] estimated this consumption on the basis of variations in fire weather indices generated from climate data, but this approach does not account for deeper burning of organic layers that can occur. In their paper, *Soja et al.* [2004a, 2004b] explore how assumptions regarding the depth of burning of the ground layer affect total emissions from boreal forests in eastern Russia. They show that moderate level of ground-layer burning increases total carbon emissions by 66% and high level of ground-layer burning increases it by 270%. While the moderate ground-layer burning scenario of *Soja et al.* [2004a, 2004b] produces estimates that are similar to those of *Hoelzemann et al.* [2004], they are substantially higher than those of *Ito and Penner* [2004], perhaps because of the coarse resolution of the analysis in the work of Ito and Penner. Another important characteristic of fires in the boreal region is incorporated into the trace gas estimates presented by *Soja et al.* [2004a, 2004b]. Field and laboratory measurements have both shown that the emission factors for smoldering combustion are much higher than those for flaming combustion for the fuel types common to the boreal region [*Cofer et al.*, 1998; *Yokelson et al.*, 1997]. *Kasischke and Bruhwiler* [2002] first argued that most of the ground-layer organic matter is consumed during smoldering combustion, and this has to be accounted for when estimating trace gas emissions. This argument was adopted in the modeling approach of *Soja et al.* [2004a, 2004b]. As a result, the CO emissions from eastern Russia produced by *Soja et al.* [2004a, 2004b] are higher than those reported by *Hoelzemann et al.* [2004].

2.3. Improving Estimates of Emissions From Biomass Burning

[25] The discussions presented in the previous sections highlight the fact that even though scientists now have access to data sets that provide information on the spatial and temporal patterns of burned area, considerable challenges exist in terms of estimating emissions from wildland fires and biomass burning. The differences in approaches used to estimate emissions are an outgrowth of the fact that improved information is needed in several critical areas, including: (1) the spatial and temporal distribution of available fuels, (2) variations in the moisture contents of fuels, (3) in forests, the types of fires that occur (e.g., surface versus crown), and (4) in boreal and some tropical regions, the degree to which peatlands and forests with deep organic soils burn and the depth of burning in these ecosystems [see, e.g., *Turetsky et al.*, 2002; *Page et al.*, 2002].

[26] Analyses of satellite imagery offer the potential to provide additional information that can be used in estimating emissions from biomass burning, including the mapping of forest and vegetation types and amount of green vegetation present, as was demonstrated by *Hoelzemann et al.* [2004] and *Ito and Penner* [2004]. Satellite data can also be used to estimate fuel loads via estimation of net primary production [*van der Werf et al.*, 2003] and to estimate fire type and fire severity [*Isaev et al.*, 2002; *Michalek et al.*, 2000].

[27] Remotely sensed data also have the capability of directly providing information on fuel moisture, as was demonstrated by *Chuvieco et al.* [2004], who showed that satellite-observed variations in surface reflectance and surface temperature were highly correlated to field measurements of moisture content in grasslands and shrublands. This study clearly points toward an emerging field of study important in improving estimates of combustion factors via satellite observations. Given the large areas of grasslands and shrublands that burn globally, continuing this line of research could provide important benefits. *Korontzi et al.* [2003a, 2003b] showed significant seasonal variations in emissions for products of incomplete combustion in tropical savannas.

[28] Two questions that are commonly asked concerning emissions estimates are: (1) what is the level of uncertainty in the estimates? and (2) where should future research be focused in order to reduce these uncertainties? The research presented in the work of *French et al.* [2004] addresses both of these issues. In this paper a Monte Carlo simulation approach was used to estimate uncertainties associated with estimating emissions from wildland fires in interior Alaska on the basis of the results from *French et al.* [2002]. Uncertainties were estimated through specifying a range in standard deviations expected for each term used to estimate emissions. The Monte Carlo approach allows one to examine all possible emissions outcomes on the basis of assuming a statistical distribution for each term and to derive a distribution of estimated emissions, from which an uncertainty term can be calculated. In addition, this approach allows one to identify not only which term in the emissions model adds the most uncertainty to the estimate, but through sensitivity analyses, one can identify how the relative reduction in the uncertainty in one parameter will decrease the overall uncertainty in the emissions estimates. Such an approach would be extremely beneficial in prioritizing future research efforts.

3. Findings and Recommendations

3.1. Estimating Global Emissions From Biomass Burning

3.1.1. Findings

[29] Current approaches for estimating global emissions are limited by accurate information on area burned and fuel available for burning. Recent burned-area products developed from satellites and from a compilation of ground-based data provide the basis for several ongoing efforts to produce new estimates of global biomass burning emissions. Further improvements in global estimates will be

based on advanced information products from regional/biome specific studies.

3.1.2. Recommendation

[30] An intercomparison between global- and regional-scale models should be carried out in the near term in order to provide the user community with the means to assess the usefulness and uncertainty of emissions estimates. The estimated emissions and range of emissions should be used in a global model intercomparison study in order to assess the consistency between estimated emissions and observations of atmospheric constituents.

3.2. Estimating Emissions From Biomass Burning in Tropical Forests

3.2.1. Findings

[31] The accuracy of estimates of emissions from fires in tropical forests is low due to: the complexity of (1) mapping active fires in this biome using satellites; (2) estimating seasonal area burned; and (3) quantifying the levels of fuels available for burning, which varies between: (1) different regions and forest types and (2) as a function of land use practice.

3.2.2. Recommendation

[32] Reducing uncertainties in estimates of biomass burning emissions requires continuation of research efforts to address all these issues in all the major areas where tropical forests exist (South America, Africa, and Asia). Particular attention needs to be paid to producing reliable and accurate estimates of burned area. In addition, the effects of land conversion to agriculture and the incremental reduction in fuel loads over burning during multiple years need to be better quantified.

3.3. Estimating Emissions From Biomass Burning in Savannas and Shrublands

3.3.1. Findings

[33] Studies focused on estimating emissions from savannas/shrublands are well advanced, and the means to produce estimates of seasonal area burned in this biome should emerge over the next several years. Through a coordinated effort the scientific community should be able to produce improved estimates of emissions from this biome over the next 2–3 years.

3.3.2. Recommendation

[34] Efforts to produce a global area burned (burn scar) products from systems such as MODIS and SPOT-VEGETATION need to continue, along with the appropriate validation activities. Attention needs to be given to variations in emissions within the burning season as a function of fuel moisture and completeness of combustion and emissions from land use fires. A coordinated program directed toward development and comparison of estimates of emissions for savanna regions should be instituted.

3.4. Estimating Emissions From Biomass Burning in Temperate Forests

3.4.1. Finding

[35] The fire science and management communities have carried out the numerous studies of fires and fuel loads in temperate regions that provide a basis for estimating emissions from vegetation fires. While this community has also maintained records on fire activity that produce some information on area burned, these data sets do not document all types of fire, nor has the accuracy of these data been assessed. Thus the ability to generate accurate estimates of emissions in this region is not high at this time.

3.4.2. Recommendations

[36] Efforts are needed to document and quantify the area burned in the temperate forest region, including: (1) urging a more complete accounting of area burned in all vegetation types by individual countries, rather than just reporting forest area burned; and (2) integration of satellite observations of fire activity with traditional methods of fire mapping to produce improved area burned estimates. Fuel load and/or biomass/carbon density maps need to be generated for all temperate regions where fires occur, as well as information on fire type and fire severity. These efforts should be carried out at a regional level (e.g., Europe/western Russia, southern Asia (particularly Kazakhstan, Mongolia, and China), and the conterminous United States).

3.5. Estimating Emissions From Biomass Burning in Boreal Forests

3.5.1. Findings

[37] Efforts to produce burned-area products through the integration of ground-based data records and satellite data products are well underway in most of the boreal forest region. On the basis of existing forestry and soil databases and existing fire behavior models, improved estimates of emissions from boreal fires are now being produced. Major uncertainties in these estimates exist due to: (1) uncertainties in area burned for western Russia; (2) documenting the patterns of fire behavior and fire severity; and (3) quantification of the levels of consumption of surface fuels, particularly the consumption of organic soils in forests underlain by permafrost and boreal peatlands.

3.5.2. Recommendations

[38] Generation of more accurate fire maps for western Russia using satellite imagery needs to be carried out. A burned-area map for all of Russia back to ~1980 should be generated using AVHRR data. Comparison and integration of different satellite and ground products in North America should continue. A systematic refinement of fire behavior, fire severity, and fuel consumption models using satellite data should carried out. Studies of the area of peatland burning and levels of ground-layer organic matter burned need to be initiated.

3.6. Improved Communication and Coordination Between the Modeling and Observation Communities

3.6.1. Findings

[39] The attendees concluded that the communication between the atmospheric modelers and those responsible for generating remotely sensed data products and emissions estimates that occurred during the workshop was extremely useful. The information requirements from the atmospheric modeling community in terms of the characteristics of the necessary data sets to provide improved emissions estimates are not well developed. The input products used in emissions modeling and the model outputs

are often unvalidated (i.e., with no known accuracy), which hinders their quantitative use.

3.6.2. Recommendations

[40] There is the need for a continued dialogue between the atmospheric modeling community and the remote sensing and emissions modeling communities to guide the improvement of the products and their use. There is a need for a clearly articulated and supported set of observation and data requirements from the emissions modeling community. The products generated by the remote sensing community, the ground-based maps and estimates, and the emission model outputs need to have associated quantitative accuracy statements and recommended guidelines for data use. Involving regional scientists with local knowledge on fires and biomass burning emissions in the development and assessment of product accuracy is strongly recommended. The proposed model intercomparisons identified above would provide an opportunity to address data requirements and product accuracy.

3.7. Operational Provision of Data Sets to Estimate Biomass Burning Emissions

3.7.1. Findings

[41] Currently, the generation of biomass burning emissions estimates and the associated data sets fall within the research community. The satellite data sets are largely experimental. Research projects are short term and cannot be relied upon for continued data provision. The provision of long-term, multiyear, validated data sets of emissions are needed for global change research and the policy communities. The roles and responsibilities for the provision of operational long-term data sets on fire emissions are currently unclear.

3.7.2. Recommendations

[42] The funding agencies are encouraged to support research into improving global biomass burning emissions and their impact on atmospheric chemistry. As the methods and techniques for emission estimates become robust, there is a need to transition them to a more operational environment and secure the long-term provision and stewardship of data sets on biomass burning emissions. The appropriate national and international operational agencies responsible for the provision and management of biomass burning emissions data need to be identified and a strategy developed for long-term operational global data set provision, validation, compilation, and management.

3.8. Utilization of Data Sets to Support International Policies

3.8.1. Findings

[43] Data sets are needed to support the formulation of policies for sustainable management of the Earth system to reveal those human-induced changes of fire regimes, fire-induced degradation of ecosystems, and land-use systems that result in exceeding natural or acceptable budgets and environmental and humanitarian impacts of vegetation-fire emissions, including the impact of smoke on human health. The implementation of international conventions and strategies that address the prevention or mitigate the negative consequences of vegetation-fire emissions require a multisectoral and interdisciplinary approach and need to be supported by data sets. There is a need for an improved interface between the science and policy communities to facilitate effective use of the data sets, e.g., through such mechanisms as a clearing house for information, and the development of regional networks of fire information providers and users.

3.8.2. Recommendation

[44] The information requirements for the implementation of international conventions and strategies that address the negative impacts of vegetation fires must be formulated jointly by the research community, the international conventions, and the agencies and programs of the United Nations (UN) and other international bodies involved in sustainable management of the Earth system. The UN and the donor community are encouraged to actively support international coordination efforts by the UN International Strategy for Disaster Reduction (ISDR), Working Group on Wildland Fire, and the GTOS GOFC/GOLD Program in their coordinating efforts at global and regional levels to reach consensus in the formulation of procedures and methodologies to further develop and utilize vegetation fire data sets for the benefit of humankind.

4. Concluding Remarks

[45] The importance of quantifying global emissions from biomass burning was highlighted by the extraordinarily large fire events that occurred during the 1997/1998 El Nino. The global impacts of these fires on atmospheric CO were first noted by *Langenfelds et al.* [2002]. The fact that the global CO anomaly consisted of three distinct emissions events separated in space and time was shown by *Novelli et al.* [2003], and *van der Werf et al.* [2004] demonstrated how interannual variations in biomass burning emissions were the driving force behind the anomalies. However, the inverse modeling study conducted by *van der Werf et al.* [2004] suggests their modeling approach significantly underestimated variations in emissions from biomass burning.

[46] Figure 1 presents a plot of the interannual variations in the atmospheric CO growth rate that clearly shows the influence of the 1997/1998 fire events. It is interesting to note that while the majority of biomass burning emissions came from fires in Africa, the greatest variations in atmospheric CO growth rate occurred in the high Northern Hemisphere. Significant variations also were present in the tropical portions of the atmosphere. The growth anomalies in Figure 1 clearly emphasize the need to study and quantify biomass burning emissions from all regions, not just where the highest emissions occur.

[47] The results of the papers in this special issue along with those presented in other recent research reinforce the recommendations made at the July 2002 GOFC/GOLD-IGBP meeting on Improving Global Estimates of Atmospheric Emissions from Biomass Burning. In particular, efforts to conduct further scientific exchanges between those who produce satellite products and emission estimates and the users of this information are needed. Intercomparisons between emissions estimates are particularly

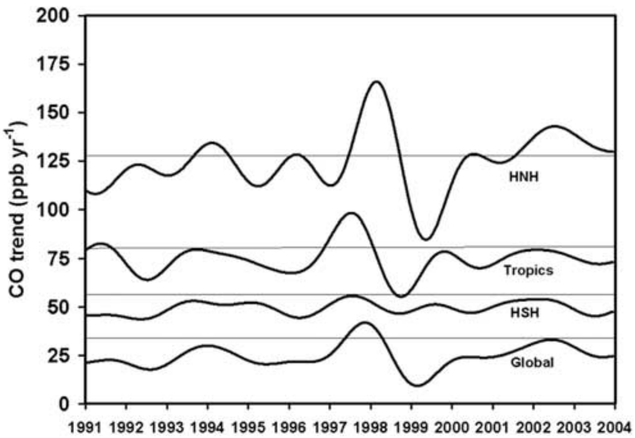

Figure 1. Averaged trend lines for atmospheric CO derived from data collected by NOAA's Climate Modeling and Diagnostics Laboratory in Boulder, Colorado. The data were created by averaging weekly samples collected from flasks in all stations (global), those from the high Southern Hemisphere (HSH, those above 30°S latitude), the tropics (stations between 30°S and 30°N latitudes) and the high Northern Hemisphere (HNH, those above 30°N latitude). The data were created by first deriving the deseasonalized, long-term trend line, and then calculating the growth rate as the time derivative of the trend line. The resulting trends are all plotted on the same graph by adding a constant to the data from each region. The horizontal lines represent the zero line for each region. (Data courtesy of Paul Novelli and Lori Bruhwiler of NOAA-CMDL.)

important so that coordination of efforts to improve and validate these estimates can occur in a timely and efficient fashion. Determining the accuracy of the model outputs must be given a high priority. In addition, mechanisms for the production of operational, validated products (as they reach maturity) on a continuous basis need to be identified and implemented.

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