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Fire in the Air: Biomass Burning Impacts in a Changing Climate

MELITA KEYWOOD, MARIA KANAKIDOU, ANDREAS STOHL, FRANK DENTENER, GIACOMO GRASSI, C. P. MEYER, KJETIL TORSETH, DAVID EDWARDS, ANNE M. THOMPSON, ULRIKE LOHMANN AND JOHN BURROWS

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Fire in the Air: Biomass Burning Impacts in a Changing Climate

MELITA KEYWOOD,[1] MARIA KANAKIDOU,[2] ANDREAS STOHL,[3] Q1
FRANK DENTENER,[4] GIACOMO GRASSI,[4] C. P. MEYER,[1]
KJETIL TORSETH,[3] DAVID EDWARDS,[5] ANNE M. THOMPSON,[6]
ULRIKE LOHMANN,[7] and JOHN BURROWS[8]
[1]CSIRO Marine and Atmospheric Research, Aspendale, Victoria, Australia
[2]Environmental Chemical Processes Laboratory, Department of Chemistry, University of Crete, Heraklion, Greece
[3]Norwegian Institute for Air Research, Kjeller, Norway
[4]European Commission, Joint Research Centre, Institute for Environment and Sustainability, Climate Change and Air Quality Unit, Ispra, Italy
[5]National Centre for Atmospheric Research, Boulder, Colorado, USA
[6]Department of Meteorology, Pennsylvania State University, University Park, Pennsylvania, USA
[7]Institute for Atmospheric and Climate Science, Zurich, Switzerland
[8]Institute of Environmental Physics, University of Bremen, Bremen, Germany

Fire has a role in ecosystem services; naturally produced wildfires are important for the sustainability of many terrestrial biomes and fire is one of nature's primary carbon-cycling mechanisms. Under a warming climate, it is likely that fire frequency and severity will increase. There is some evidence that fire activity may already be increasing in Western U.S. forests and recent exceptionally intense fire events, such as the Australian Black Saturday fires in 2009 and Russian fires in 2010, highlight the devastation of fires associated with extreme weather. The impacts of emissions from fires on global atmospheric chemistry, and on the atmospheric burden of greenhouse gases and aerosols are recognized although gaps remain in our scientific understanding of the processes involved and the environmental consequences of fires. While significant uncertainty remains in the long-term impacts of forest fires on climate, new sophisticated tools have recently become available (observational and modeling). These tools provide insight into changing wildfires Q2

Address correspondence to Melita Keywood, CSIRO Marine and Atmospheric Research, PMB1 Aspendale, Vic 3195, Australia. E-mail: melita.keywood@csiro.au

and intentional biomass burning activity in the Anthropocene era that is marked by humans' impact on Earth. The understanding of the impact of wildfires and intentional biomass burning emissions on the present and future climate is reviewed. Presently, fires and their emissions are controlled under fire management and emission reduction schemes. Under future climate conditions, significantly more effective controls on these fires seem necessary. Continued and improved monitoring to support and to demonstrate the effectiveness of the adopted measures, and further deepening of knowledge on the mechanistic and sociological factors that influence fires and their environmental impacts is highly needed. Wildfires and biomass burning are important for a range of international and domestic policies, including air pollution, climate, poverty, security, food supply, and biodiversity. Climate change will make the need to coherently address fires based on scientifically sound measurements and modeling even more pertinent Q3

Q4 **KEY WORDS:**

INTRODUCTION

Wildfires and the intentional burning of biomass are an integral part of Earth's system since they occur in all major biomes with diverse and broad environmental impacts. At the surface, fires influence the composition of plant species and hence indirectly, the type of biome,[1,2] change surface energy fluxes, and affect the atmospheric water cycle with removal of vegetation and changes to vegetation types.[3] While they can recycle nutrients to ecosystems located downwind they also damage ecosystems, property, infrastructure, and human life. Trace gases and aerosol fire emissions influence atmospheric chemistry, radiative processes, and cloud formation,[4–6] and can contribute to local, regional, and global pollution. Predicting the occurrence and magnitude of fires is an important challenge and the subject of significant research activity, with tools and methodologies continually being developed to refine the understanding and hence the ability to predict fire occurrence in a changing climate.

Fires have been suggested to influence the evolution of some biomes, such as the expansion of savanna ecosystems during the Miocene, 6–8 million years ago.[1,7] Naturally produced wildfires are important for the sustainability of many terrestrial biomes. In boreal forests fire is a factor in determining the age, species, diversity, and mixture of vegetation types, as well as energy flows and biogeochemical cycles that influence the global carbon cycle. In savannas, wildfires are responsible for preventing the encroachment of forest as well as the regeneration of grassland vegetation. Fire in the natural context is an important part of ecosystem services providing nutrients and recycling material and has always provided to some extent emissions of gases and aerosols to the atmosphere.[8]

Forest, savanna, grassland, and tundra are among vegetation types susceptible to be impacted by fires. Forest alone covers between 30% and 37% of global land surface.[9,10] Thus, a large fraction of Earth's surface is susceptible to impact by fires. The circumpolar (45–70° North) boreal forests and woodlands extend to ~9–14 million km^2,[11,12] representing about 6–9% of global land surface and 30% of the world's terrestrial carbon storage.[12] Tropical forests (between 22.5° North and 22.5° South) cover 6.25 million km^2 (5% of global land surface), 49%, 34%, and 16% being in tropical America, Africa, and Asia, respectively.[9] Savannas composed of a mixture of trees and grasses ranging from open woodland to grassland cover about 33 million km^2 (22% of global land surface). Temperate forests occupy the smallest area of the forest-covered land surface (0.75 million km^2; i.e., 0.5% of global land surface) reflecting their coincidence with sites of human settlement, exploitation, and development.

Both tropical and boreal forests are important contributors to global carbon emissions when burned. The fire emissions depend on the area burned as well as the detail of the fuel type and combustion process. The frequency and severity of fire events also depends on prevailing meteorological conditions such as drought that increase susceptibility to burning. During the exceptional 1997–1998 El Niño period 26,000 km^2 of standing forests burned in the Amazon, resulting in the loss of up to 0.4 Pg of carbon,[13] double the amount of carbon lost due to deforestation in the Amazon each year.[14] The El Niño also coincided with fires in Indonesia in 1998, and 20,000 km^2 of forest (peat and surface vegetation) burnt in East Kalimantan, Borneo, with up to 2.5 Pg of carbon lost into the atmosphere, equivalent to 40% of fossil fuel global carbon emissions.[15] The same year, boreal fires burning over 13,000 km^2 in Russia were responsible for 14–20% of the annual carbon emissions from forest fires globally,[12] equivalent to 40% of the regional fossil fuel carbon emissions from Russia. Present estimates suggest that globally wildfires contribute about 20% of the fossil fuel carbon emissions to the atmosphere.[16] The 2010 Russian fires that burnt 886,126.96 ha over approximately one month are estimated to have emitted 120 Tg of carbon (including CO_2, CO, CH_4, and other smoke aerosols).[17]

Carbon emitted from fires in boreal forests is likely to have a longer residence time in the atmosphere due to the slow postfire growth rate of boreal vegetation. In contrast tropical climates with high temperatures, sufficient rainfall, and long periods with sunlight allow for more rapid vegetation growth (forest or savanna) so that carbon emitted from tropical savannas has a shorter atmospheric residence time.

Biomass burning is a source of numerous trace substances coemitted with carbon dioxide (CO_2); including methane (CH_4); carbon monoxide

(CO); nitrogen oxides (NOx); ammonia; volatile organic compounds (VOC) including oxygenated, nitrated, and halogenated compounds; carbonyl sulfide; sulfur dioxide; and carbonaceous and sulfate-containing particles.[18–22] For several substances these emissions are comparable to industrial emissions,[23] or even exceed them, as is the case of organic aerosols.[15] Contrary to the industrial emissions that often show minimal seasonality, biomass burning emissions are concentrated mostly over a particular burning period (or season).

Routine use of fire appears to have begun between 50,000 and 100,000 years ago. Hunter-gathers used fires to reduce fuel and manage wildlife and many of these practices continue today.[24] The indigenous people of Northern Australia used manwurrk (fire drives) to flush out game during hunting,[25] demonstrating the knowledge and skills indigenous people bring to fire management in fire-prone landscapes around the world.

Fires can be initiated naturally by lightning strikes, although estimates suggest that 90% of fires are intentional for land-use practices.[26] Examples include forests and savannas clearing for agricultural and grazing use; slash and burn cultivation; the control of grass, weeds, and litter on agricultural and grazing lands; removal of stubble and waste on agricultural lands after harvest; and the domestic use of biomass matter for cooking and heating.

While biomass burning has been part of slash and burn agriculture for a relatively long period, increasing population and demand for agricultural land and food has had a profound effect on the extent of biomass burning. An upward trend in global carbon emissions attributable to deforestation over the 20th century has recently been observed with Asia, Africa, and South America being the most significant contributors to this trend during the 1990s.[27] The trends in global deforestation carbon emissions reflect settlement patterns. For example, at the beginning of the 20th century, North America, Asia, and Europe accounted for the most carbon emissions due to deforestation. Between 1900 and 1960, an estimated 5% decrease in global carbon emissions is attributed to land-use changes and wood harvesting that reduce the biomass available for burning.

In this article we review our present understanding of the impact of biomass burning emissions on the present and future climate. The first section summarizes the impacts of fires on air quality, long range transport of pollutants, chemistry and atmospheric radiation in the present climate. This is followed by a discussion of the tools used to observe and predict fires and their impacts in the present and future climate. The influence of short- and long-term climate changes on fire occurrence and severity is then discussed together with limitations in our ability to predict fire ignition and behavior. Fire management and global policy issues are summarized and the paper concludes with suggestions for actions to develop the tools and data required to improve our ability to assess, adapt to and mitigate fires and their emission.

IMPACT OF FIRES IN THE PRESENT CLIMATE

Air Quality and Long Range Transport

Biomass burning plumes containing elevated concentrations of aerosols, CO, and ozone can be transported over thousands of kilometers in the tropics[28,29] and in the middle latitudes with boreal forest fire pollution plumes impacting the air quality in regions with large anthropogenic emissions, thousands of kilometers from the fires.[30] During the 2010 Russian fires air quality of Moscow was severely impacted with concentrations of particulate mass less than 10 μm in diameter (particulate matter [PM] 10) up to 500 μg m^{-3} being recorded.[31]

Although most African fires perturb the Atlantic and eastern South American environments,[32–34] emissions from southern African fires are also transported into the Indian Ocean, with particularly strong plumes reaching Australia within 8–13 days.[18] Boreal forest fire plumes are similarly transported to downwind continents[35] and circle the entire northern hemisphere.[36,37] Similarly, aerosols from Australian forest fires have been observed to circle the southern hemisphere.[38]

The number of fires in the boreal region varies substantially from year to year. During strong fire years, many individual long-range transported fire plumes mix, impacting the chemical composition of the background atmosphere. Consequently, around 60% of the interannual variability of CO in the extra-tropical northern hemisphere in summer can be explained by boreal forest fire activity in North America and Russia.[39] Biomass burning plumes can also mix with materials from other sources, thereby strengthening their impact on air quality. For instance, over and downwind of Africa, aged biomass burning aerosol plumes are often mixed with desert dust.[39]

There are multiple routes for pollution injection into different layers of the atmosphere where long-range transport subsequently takes place (Figure 1). Although much of this transport occurs just above the mixed layer, redistribution of pollution as emission by-products (e.g., CO, ozone, VOC) interacting with convection often leads to pollution layers in the upper troposphere.[40–42] Hence, in addition to the occasional introduction of aerosols and other pollutants into the stratosphere by pyrocumulus, mixtures of nitrogen oxides from lightning and resulting ozone formation can be interleaved with pyrogenic pollution, typically between 6 and 12 km altitude.[43]

Both agricultural and boreal forest fires can have a strong impact on the aerosol concentrations in the Arctic,[44–46] where pollution from black carbon (BC) contained in anthropogenic and biomass burning emissions is a major issue. Not only does BC warm the atmosphere by absorbing radiation, its deposition to the snow pack reduces the snow albedo and triggers enhanced melting.[47,48] Snow albedo changes at Arctic sites have been indeed identified during two extreme biomass burning events (Figure 2).[44–45]

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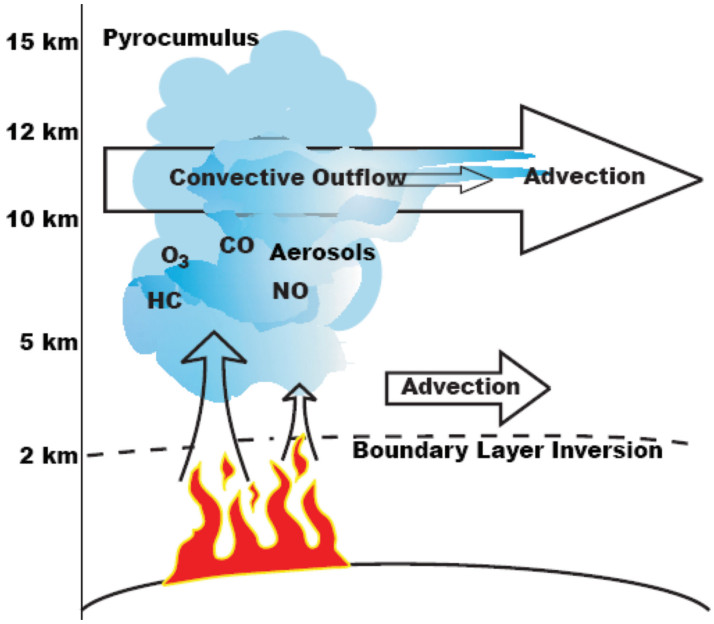

FIGURE 1. Schematic showing the injection of biomass burning emissions into atmospheric layers and their subsequent long range transport in the upper atmosphere. (Color figure available online).

Atmospheric Chemistry

The presence of many reactive species within biomass burning emissions means they can have a significant effect on atmospheric chemistry. The efficiency of biomass burning emissions to produce ozone depends on the dilution and their physicochemical transformation during atmospheric transport, as well as the colocation of other emission sources. About 10–25% of the net global photochemical production of tropospheric ozone is estimated to be due to biomass burning.[49,50] High ozone plumes extend over major parts of the tropical and subtropical continents during dry seasons with concentrations being three times higher than background conditions.[21,51] Over the Atlantic the impact is enhanced by coincident increases in anthropogenic emissions of NO_x in relatively pristine regions.[52,53] Recirculation over the Indonesian maritime continent allows smoke to accumulate and tropical tropospheric ozone to increase relative to periods without smoke.[54] Fresh fire plumes show low ozone levels due to titration from emitted NO_x,[21,55] while ageing of plumes enables the buildup of secondary pollutants, ozone, and more oxygenated species such as secondary aerosols (sulfates, nitrates, and organics).[56] Aged smoke particles show enhanced cloud condensation activity due to coating by water soluble material; condensation of VOC with multiple functional groups emitted during burning appears to be a major

a) 26 April 2006

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b) 2 May 2006

FIGURE 2. View from the Zepplin station (a) under clear conditions on 26 April and (b) during the smoke episode on 2 May 2006. Image courtesy of Ann-Christine Engvall. From Stohl et al.[45] (Color figure available online).

component of secondary organic aerosol.[57] Biomass burning emissions affect the oxidants in the troposphere, in particular the hydroxyl radical that is central to the lifetime of CH_4, tropospheric ozone, and halogens, thus impacting stratospheric ozone;[21,58] methyl bromide emitted by fires may cause ozone depletion.[59] Other potential effects on stratospheric ozone may occur via perturbation of radiation, temperature, and the provision of aerosol surfaces for heterogeneous chemical reactions. Such effects also impact the troposphere. Biomass burning aerosols are also subject to cloud processing, affecting the composition and oxidizing efficiency of smoke plumes. Increases in emissions of CO and hydrocarbons from fires together with changes in water vapor, cloud cover, and temperature may be responsible for up to 6% decreases in global mean hydroxyl radical concentration between 1997 and 1999, the main sink of CH_4.[61] A series of significant CH_4 growth rate fluctuations during the 1990s has been attributed to biomass burning in Indonesia in 1997 and Russia in 1998, affecting both the emissions of CH_4 and the concentrations of the hydroxyl radical. In addition positive CH_4 growth rates from 2000 to 2003 were coincident with boreal fire emissions at this time.[60–62] The magnitude of these effects is highly variable in space and time.[63] Due to the large spatial variability of fire plumes, the evaluation of their global impact on atmospheric composition and climate requires further investigation.

Radiative Forcing

Given the large uncertainties of greenhouse gas (GHG) and aerosol forcings in the present generation of global climate models, it is unsurprising that understanding the impact of fires on these forcings is limited. GHG emissions from forest fires are suggested to have a positive feedback on climate leading to enhanced global warming via modifications to weather and vegetation types.[11] Radiative forcing resulting from an intensive fire in boreal forest in Alaska was assessed by integrating the effects of GHG, aerosol (including BC) deposition on snow and sea ice, and postfire changes in land surface albedo and found to be dependent on time.[3] During the first year after the fires, positive forcing of 34 ± 31 W m^{-2} of forest burned was dominated by deposition of aerosols (including BC, despite a small offset by the negative forcing associated with changes to surface albedo within the fire perimeter). Over a longer time frame (80 years), net negative radiative forcing of -2.3 ± 2.2 W m^{-2} suggested the balance between persistent changes in land albedo, the effects of long-lived GHGs emitted during the fire, and continued uptake of CO_2 by the forest ecosystem.

This calls into question the role that future fires in boreal ecosystems may have in accelerating climate change and highlights the importance in understanding the interaction between land surfaces and climate in these northern forests. A comparison of top of atmosphere (TOA) radiation fluxes over boreal forests in Alaska, over different fire years, demonstrated higher TOA radiative cooling associated with fires.[64] This was attributed to higher surface temperatures and increased scattering associated with organic aerosol (with some warming due to BC) and suggests that aerosol emissions from boreal forest fires and their absorptive character are presently underestimated in models.

Primary emitted smoke particles together with the chemical formed secondary particles also affect cloud condensation nuclei number (CCN), cloud droplet size, and precipitation.[21,65,66] Specifically, smoke aerosols cool the surface and heat the atmosphere, and provide thermal stability in the lower troposphere by reducing convection and suppressing convective cloud formation. In the presence of high smoke pollution, aerosols increase the number of CCN leading to reduced cloud droplet size so that the onset of precipitation occurs at greater heights above the cloud base compared with clouds that form in clean air condition.[65] Satellite observations indicate that heavy smoke conditions eliminate scattered cumulus cloud cover, regionally leading to atmospheric warming rather than cooling.[66] Emissions of biogenic VOC from boreal forests produce SOA that form CCN, so that boreal forests have an indirect effect on radiative forcing by impacting on cloud-albedo dynamics.[67] Boreal forests were found to double the regional CCN concentrations causing a change in radiative forcing of between -1.8 and -6.7 W m^{-2} or an overall cooling. However, since fires also result in the removal of biogenic VOC emission sources, the boreal forest potential cooling effect may be impacted. This added complexity highlights the uncertainty in our understanding of the long-term impacts of forest fires on climate.

Pyroconvection

Heat and water vapor emissions from strong forest fires support the development of extremely deep convection. The heating of the surface and the initial buoyancy of the biomass burning plume generate strong updrafts above fires that are responsible for convective transport of tracers in the free troposphere where inefficient removal processes and fast winds can disperse the smoke plume over long distances.[68] Pyroconvective events reaching stratospheric altitudes are frequent in the temperate and boreal forests of North America[36,43] and Siberia,[69] as well as in Australia.[70] Even single events can double the zonally averaged aerosol optical depth (AOD) in the lowermost stratosphere, with the smoke persisting at these altitudes for months.[71] Aircraft measurements have confirmed the presence of smoke and gases in the stratosphere at altitudes of 16 km and potential temperatures above 380 K,[72] where most of the atmosphere's ozone is located.

Pyroconvection is not generally captured by present global models. Emission altitudes are specified either climatologically or as a function of some observable quantity (e.g., fire radiative power). Many models assume fire emission to be injected into the lowest model layer, leading to large errors.[73] Some special high-resolution models have recently proved skilful,[74.75] and in some projects such as AEROCOM plume altitudes have been prescribed.[76]

TOOLS FOR ASSESSING BIOMASS BURNING PRODUCTS AND IMPACTS

Almost 30 years after the pioneering work by Crutzen et al.[4] that recognized the impact of biomass burning on global atmospheric chemistry, an improved understanding of pollutant emissions from fires and their impact on atmospheric composition has been acquired. A number of research coordination activities contribute to the understanding of biomass burning, including the Global Fire Monitoring Center and the European Commission via the Forest Fire Information System, both of which facilitate monitoring and assessment of biomass burning activity. Significant effort has been focused within the context of international field campaigns sponsored by the International Global Atmospheric Chemistry (IGAC) project, the International Geosphere-Biosphere Project (IGBP) and the International Commission of Atmospheric Chemistry and Global Pollution.[19,51,65] During the 1990s a series of international and interdisciplinary research campaigns on biomass burning in tropical, subtropical, and boreal biomes was conducted under the IGBP-IGAC umbrella. The Biomass Burning Experiment resulted in a deeper understanding of the production of chemically and radiatively important gases and aerosol species from vegetation fires to the global atmosphere and their effect on regional and global chemistry. Because of the diversity of scientific approaches to the biomass burning research, including recent advances in remote sensing products, advances in fire and atmospheric modeling, advances in forecasting systems used for emergency response, and the inclusion of the interaction of fire regimes with vegetation in some climate models, the Biomass Burning Experiment as a large-scale international and almost global collaborative effort has subsequently been replaced by numerous small-scale projects and campaigns.

Observational Tools

To avoid undesirable consequences of fires, prevention, monitoring, and management of fires are required. Information on fire behavior (from ignition to cessation of burning) and location is vital for the prediction of fire occurrence and emissions. Methodologies used to acquire information on fire behavior have included laboratory experimental programs and in situ observations. Dedicated field campaigns have been particularly important for linking surface combustion processes to regional plume development through a combination of ground-based and aircraft observations. The Transport and Atmospheric Chemistry Near the Equator–Atlantic field mission was an investigation of the chemical composition, transport, and chemistry of the atmosphere over the tropical South Atlantic Ocean and the adjacent South American and African continents.[77] Coincidently the Southern African Fire-Atmosphere Research Initiative (SAFARI-A) investigated the emissions from fires and soils in southern Africa, the meteorology over the subcontinent, and the ecological impact of fires in the African savanna.[78] These experiments demonstrated that widespread biomass burning in both South America and southern Africa is the dominant source of the precursor gases responsible for the formation of the large amounts of ozone observed over the South Atlantic Ocean[79] and that the meteorology in the region favors the accumulation of the precursor pollutants over the tropical Atlantic basin resulting in the in situ production of ozone by photochemical processes.[42] SAFARI 2000 carried out in southern Africa in 2000 and 2001 addressed a broad range of phenomena related to land-atmosphere interactions and the biogeochemical functioning of the southern African system.[80] It included the generation of new and revised biogenic and pyrogenic emission factors; airborne characterizations of aerosols and trace gases; regional haze and trace gas characterization; and radiant measurements by surface, aircraft, and remote sensing platforms. SAFARI 2000 resulted in significant insights into the regional scale biogeochemical cycling of southern Africa and contributed to the validation of remote sensing instruments on board the NASA Terra spacecraft.[81]

Remote sensing from satellites is the best method for acquiring quantitative information on the global magnitude and spatial distribution of biomass burning. Remote sensing data include observations of fire activity (ignition, location, and burnt area) and products such as temperature, precipitation, solar radiation, vegetation type, and Normalized Difference Vegetation Index that when fed into biogeochemical models or used with vegetation classification systems enable evaluation of fuel load and combustion completeness.[82] In addition remote sensing also generates data on pollutants emitted by biomass burning (see IGACtivities March 2007 Newsletter[83] for a detailed description of satellite based instrument presently available for the measurement of fire activity and pollutant concentrations). Figure 3 shows an example of some remote sensing products, particularly the spatial distribution and seasonal variation of southern hemisphere biomass burning derived from observations made with the Terra satellite, including CO mixing ratios from the Measurement of Pollution in the Troposphere (MOPITT) sensor and AOD and fire counts from the Moderate-Resolution Imaging Spectrometer (MODIS) between September 23 and 30, 2003.[18] Figure 4 shows near real-time remote sensing observations of the 2010 Russian wildfires with smoke and clouds derived from Atmospheric Infrared Sounder visible wavelength radiance data overlying CO concentrations. Figure 5 shows AOD data

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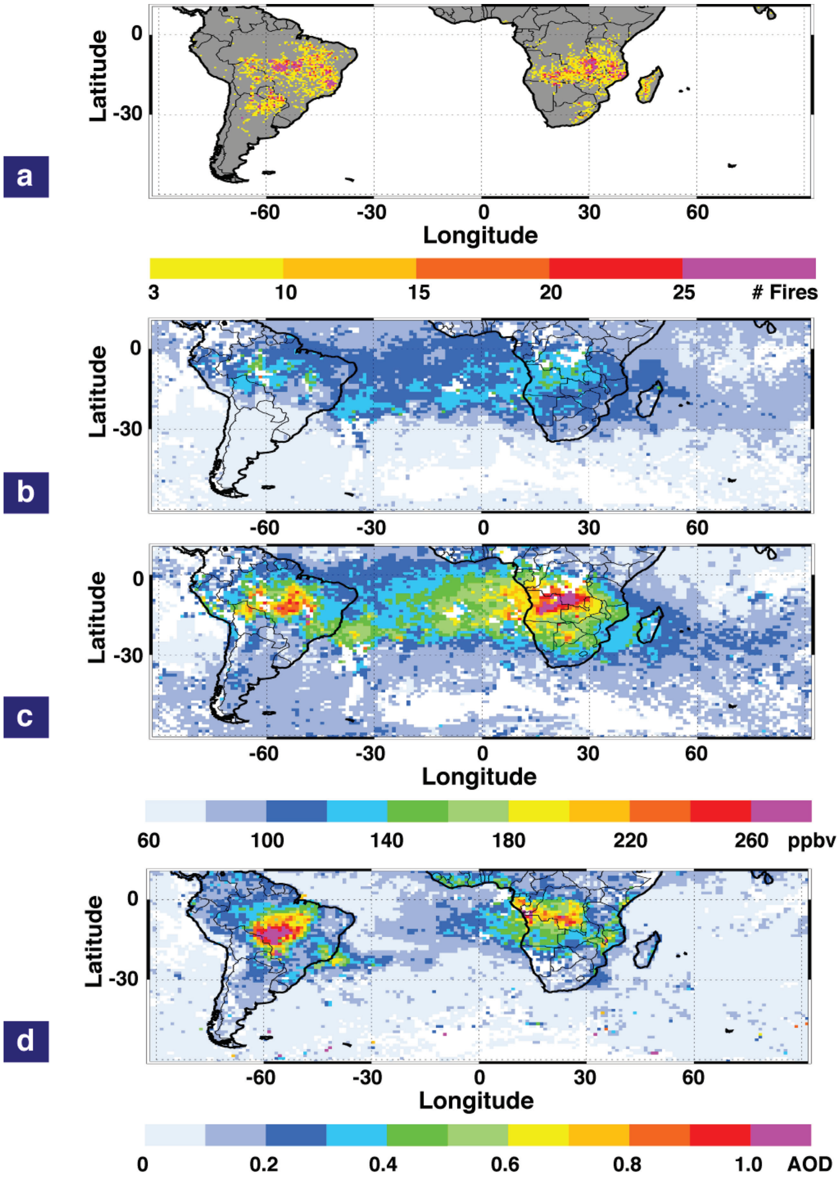

FIGURE 3. Mean distributions of (a) MODIS fire counts, MOPITT CO mixing ratio (ppbv) at (b) 250 hPa and (c) 700hPa, and (d) MODIS fine mode AOD for September 23–30, 2003.[18] (Color figure available online).

from MODIS that track the extent of smoke from central Russian wildfires averaged over the five-day period from July 27 to 31, 2010.

A number of satellite-based observations have been available since early 1982 to constrain fire activity from space.[84] The majority of satellite-based sensors employ passive techniques, observing either solar backscatter or

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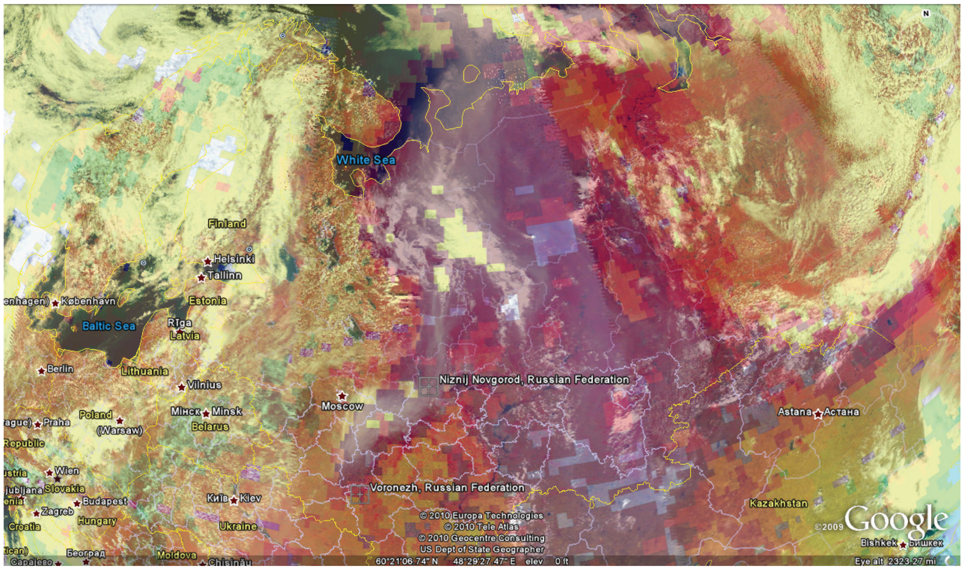

FIGURE 4. Image of Atmospheric Infrared Sounder visible wavelength radiance data (foreground), showing clouds and smoke from Russian wildfires, and overlying CO concentrations (background). Dark red indicates CO concentrations higher than 120 ppb. (Color figure available online).

thermal emission. The main biomass burning products derived from remote sensing include fire activity (or hotspots) and area burned. Fire activity provides information on the spatial and temporal distributions enabling near real-time fire monitoring. The duration of a fire can be estimated since in general small fires can be detected. However, fire activity may be masked by cloud cover and smoke. The advantage of the area burned products over active fire detection is that observational gaps due to cloud cover and satellite revisit time can be filled due to the persistence of the burn scar. However area burned may be underestimated since a substantial part of the grid cell has to be burned in order to be counted. The advantages and limitations of fire activity and area burned products suggest that the combination of these products would improve global estimates of biomass burning emissions.[82,85]

Table 1 lists the fire activity and burned area products presently available. Products have progressed from single to multiyear enabling an understanding of interannual variability in area burned with the combination of regional active fire and burned area data as in the Global Fire Emissions Database version 2 (GFED v2) and version 3 products.[16,82] The recently developed burned area product L3JRC[86] demonstrates both the progress and the remaining limitations in our ability to monitor fires. The accuracy of the burned area product is dependent on vegetation type, highlighting limitations in the algorithms used to derive burnt areas from reflectance data produced

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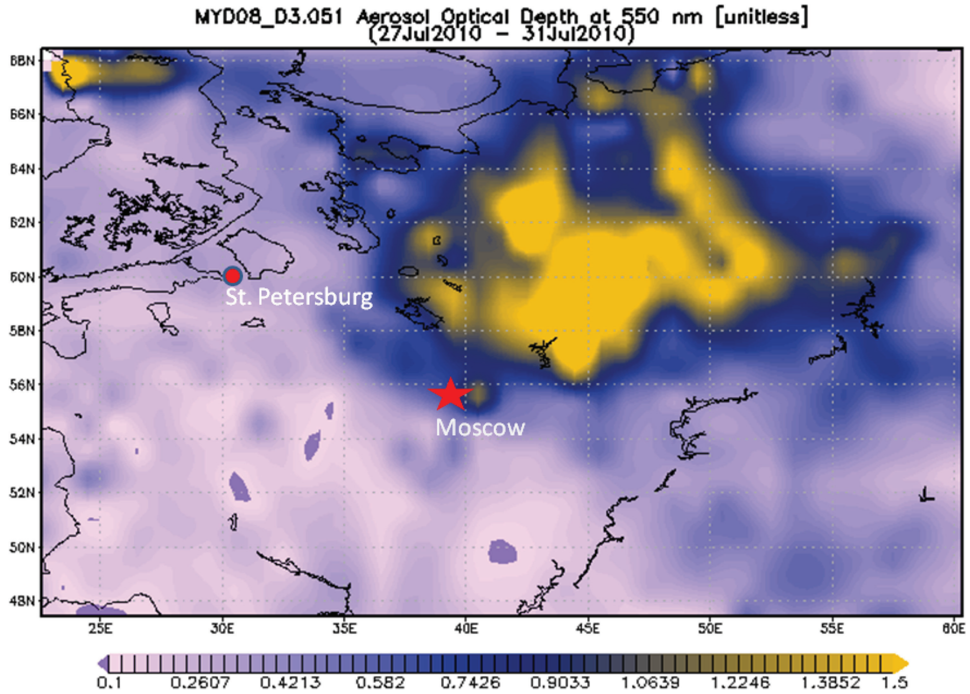

FIGURE 5. Aerosol optical depth at 550 nanometers data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the EOS Aqua satellite, showing the extent of smoke from central Russian wildfires. The MODIS data were averaged over the five-day period July 27–31, 2010. (Color figure available online).

by the SPOT VEGETATION sensor.[86] Over areas with low vegetation cover, the amount of area burned is significantly underestimated. In addition, the low-intensity fires in sparse vegetation reveal only a subtle change at middle infrared wavelengths. The ability to detect small burn scars is also limited, particularly over cultivation and managed areas. Use of active fire data and reduction in the grid sizes used in the algorithm and for validation could improve this limitation.

In addition discrepancies in burned areas derived from different sensor products result in differences in emission estimates of pyrogenic chemical species. For example, a validation of GLOBCARBON, MODIS, and L3JRC burned-area products using standard independent reference data and reporting protocols for Southern Africa showed that the MODIS product had the highest accuracy, most probably due to MODIS's higher spatial resolution that enables the detection of smaller and fragmented fires.[87] The ACCENT Biomass Burnt and Satellite Observations Project is an intercomparison focusing on total PM and CO emission estimates. Preliminary results demonstrate differences of a factor of two in CO emissions derived using the L3JRC burned area product, the MODIS fire count product and the Global

TABLE 1. Remote sensing products of area burned and fire counts

	Satellite/Sensor	Coverage
Burned area products		
Global Burned Area (GBA) 1982–1999[170]	Polar NOAA-AVHRR	Global 8 km weekly
GBA 2000[171]	Polar SPOT VEGETATION	Global 1 km monthly
GLOBSCAR 2000[172]	Polar European Remote Sensing Satellites (ERS) Along Track Scanning Radiometer (ATSR)	Global 1 km monthly
L3JRC 2000–2007[86]	Polar SPOT VEGETATION	Global 1 km daily
Global Fire Emissions Database version 2 (GFED v2)[82]	Polar MODIS (2001 onward), TRMM-VIRS and ATSR (for the pre-2001 period), and burned area (MODIS)	In 0.5 km monthly 1997–2006
GFED v3[16]		In 0.5 km monthly 1997–2009
Global Carbon Burnt Area Estimate (BAE)[173]	VEGETATION, (A)ATSR and MERIS	Monthly 1998 to 2007
Fire count products		
TRIMM[174]	Polar Tropical Rainfall Measuring Mission (TRMM)—Visible and Infrared Scanner (VIRS)	0.5° × 0.5°, between 38 °N and 38 °S since January 1998
World Fire Atlas[175,176]	Polar European Remote Sensing Satellites (ERS) Along Track Scanning Radiometer (ATSR)	Global in 1 km × 1 km daily since July 1996
MODIS[82]	Polar MODIS	In 1 km × 1 km on daily basis since 2001
Fire counts and fire radiative power 2004[88]	Geostationary Spinning Enhanced Visible and Infrared Imager (SEVIRI) Meteosat-8 satellite	Africa 3 km in 15 minutes

Burned Area 2000, and marked differences in the timing of peak burning periods.[55]

Spatial and temporal resolution is of particular relevance for monitoring of fires. Polar orbiting satellites, while having good spatial coverage of fires, provide only limited information on the temporal evolution of fires. Conversely, geostationary satellites produce data with high time resolution and poor spatial resolution. Hence, there is a need to combine the information derived from both satellite types when considering the significant diurnal cycle displayed by fires[88] and the requirement to link emissions estimates to models of atmospheric transport and chemistry.

Emission Estimates

To estimate biomass burning emissions, burned area products are combined with information on fuel loads, combustion completeness, and emission factors. Biogeochemical models are used to determine fuel loads and combustion completeness[82,85,89–91] and in situ observations provide information on emission factors.[19]

Biogeochemical models estimate aboveground biomass levels and incorporate process level information on vegetation and fuel accumulation and removal. For example a fire module in the Carnegie-Ames-Stanford-Approach estimated global variations in fire emissions over an El Niño–Southern Oscillation (ENSO) cycle.[62] Regional applications of biogeochemical models improved emission estimates from the combustion of belowground fuels in boreal regions[92] and in tropical regions, particularly the Indonesian drained peats, which released large quantities of carbon to the atmosphere during the 1997–1998 El Niño.[15]

Emission factors (EFs) are usually defined as grams of trace gas emitted per kilogram of dry matter consumed during a fire. Emission factors for over 100 chemical components have been experimentally determined, compiled, and critically reviewed for a range of biomes.[19] However, several important features of fires that influence the amount of material emitted by the fire may not be captured in many EFs used in these estimates, including the fire phase, the flaming (F) and the smoldering (S) phases. The ratio of F/S occurrence depends on fuel conditions, fire weather, and terrain slope. In addition, variation in timing of fires (or seasonality) is responsible for variation of EF within a biome. In general, drier fuels in late season fires result in more complete combustion[82] and in some biomes this may manifest as changing EF as the season develops and fuels become drier (e.g., savannas) or the commencement of burning not occurring until late in the season when fuels are dry enough (e.g., tropical and subtropical forests). Emissions of CH_4 from fires in southern Africa were found to be disproportionately higher in the early fire season suggesting the bulk of CH_4 emissions result from early season fires.[93,94] However, the actual magnitude of this effect is presently unclear and requires field measurement in a wider range of savanna plant communities around the world. To date, all analyses of seasonality rely on derived relationships between moisture content of fuel (denoted by a greenness index) and combustion efficiency (i.e., there are presently no comprehensive measurements of the seasonality of emissions composition). However, it is likely that interaction between the mix of grass, forest litter, coarse and heavy fuels, and fuel moisture on combustion efficiency will result in EF seasonality that is regionally specific. For example, in the Australian savanna fuels tend to be fully cured before burning commences in the early dry season and therefore the strong seasonality reported elsewhere[93] probably does not occur to the same extent in Australia.

The accuracy of bottom-up accounts of emissions has not yet been assessed globally and regional consistency and accuracy is debatable. For northern Australia, for example, an underestimate by about 50% have been deduced comparing a verified regional account[95,96] with earlier emission estimates[90] for the year 2000, while GFED v2 emissions[82] were more consistent. For the entire Australian continent, however, GFED v2 is substantially higher than National Estimates[97] possibly due to the application of a coarse vegetation map resulting in crop stubble burning being misidentified as forest fires. However, both global data sets are valuable as indicators of fire variation in the location, intensity of biomass burning emissions, and their significance relative to fossil fuel combustion. These examples highlight the importance of including regional information into global data sets, suggesting that understanding regional features of burning behavior is an important research priority.

Inverse modeling techniques that combine atmospheric data on trace gases and particles may also reduce uncertainties in emission estimates. Data from the MOPITT sensor were used to identify several areas where previous estimates of biomass burning emissions were inadequate[98] and MOPITT observations provided additional constraints on the seasonal timing of fire emissions in the Southern Hemisphere, especially in southern Africa.[99] Both studies concluded that bottom-up inventories significantly underestimate total emissions and found substantial differences in the seasonality of emissions from the inventory predictions.

The accumulation of uncertainties at virtually every step in the process results in a factor of two variations in global estimates of carbon emissions from fires.[55,84] However, the recent development of new algorithms that quantify fire radiative power from satellite data[88,100] shown to be directly related to fuel consumption by fires, have the potential to significantly reduce uncertainty associated with fuel loads and combustion completeness and thus reduce the overall uncertainty in fire emission estimates.

Earth System Models

The increasing availability of satellite products, burned area, and active fire counts that can be used as proxy for fire events and their emissions in the atmosphere has enabled the construction of time dependent biomass burning emission inventories[82,90,101–103] for use in large-scale chemistry-transport atmospheric models. A methodology to derive wildfire emissions for use in air quality models, based on assimilation of satellite observations of temperature anomalies and of fire radiative powers that are converted into emission fluxes by empirical emission factors,[104] has relatively low accuracy for small fires. Improvements of such models require refining of the emission factors globally, determination of the types of fires (smoldering or flaming), evaluation of the injection heights of the plumes, and predicting the temporal evolution of fires.

Due to the importance of fires for the environment and their link to climate, recent developments of Earth System Models concern the inclusion of fires in these models. However, it is challenging to predict both natural and anthropogenic ignition of fires, as well as anthropogenic fire suppression. A few models have begun to characterize global fire occurrence. The procedures used to estimate fire activity differ and are based on topsoil layer Q8 moisture content and dead fuel amount (shown by Thonicke et al.) on fuel availability and fuel moisture, and presence of an ignition source (anthropogenic or natural by lightning)[105] or on fire danger indices such as the Nesterov fire danger index.[106] Fire danger indices are based on meteorological parameters such as temperature, humidity, and precipitation and have been shown to be well correlated with area burned in North America and Russia over the 20th century.[107] This suggests they may prove to be useful indexes of fire danger in future climate conditions.

While simple generalized models may omit many fine details that are important for predicting fire behavior on small scales, such as spatial availability of fuels of different ignitability, at a global scale these details may be hard or even impossible to quantify so that their inclusion in global models may actually increase global model uncertainties. A simple generalized fire model for all biomes for use in global climate models has recently been developed.[108] It determines flammability conditions from vegetation density and a set of available meteorological parameters: precipitation, relative humidity, and temperature. A ubiquitous ignition source is assumed or alternatively the ignition source incorporates both natural and anthropogenic sources, as well as anthropogenic fire suppression. When evaluated by comparison with calculated fire counts with satellite multiyear records the algorithm was able to reasonably reproduce the global fire patterns and their seasonal variations that are driven by vegetation cycles and climate conditions. However, the anthropogenic influence has very substantial global footprints on fire seasonality, Q9 due to specific timing of ignitions for land-use purposes.[174] This is not sufficiently captured by the models that, at present, perform poorly in representing the human impact on fire frequency through deforestation, agriculture, and fire management practices.

Adequate representation of the anthropogenic influence on fires requires not only information on population density, but also comprehensive global socioeconomic data on sources of anthropogenic ignitions, fire suppression policies and resources, and degrees of fire management. Much of this information is presently not available. However, the biogeochemical Q10 model CLM-CN[27,109] accounts for the fraction of deforestation that occurs due to burning by incorporating land use change scenarios and the role of humans in modulating wildfires (by suppression or ignition). Using this approach, global fire carbon emissions have been simulated to range between 2.0 and 2.4 Pg of carbon per year for the period 1997–2004 (for the same period GFED v2 and GICC report 2.3 and 2.7 Pg of carbon per year, respectively). Q11

IMPACTS OF CLIMATE CHANGE ON BIOMASS BURNING

The link between long-term climate change or short-term variability and fire activity is complex with multiple feedbacks expected (and potentially unknown). Fires require fuel to burn and the type, quantity, and quality of fuel is influenced by climate. Periods of high precipitation or high CO_2 loadings may result in increased biomass growth so that enhanced fuel loads are available in future fire seasons. Reduced water availability associated with drought may result in drier biomass that is more readily burned in possibly more intense fires. Higher temperatures and other extreme weather may lengthen fire seasons and result in increased likelihood of fires ignitions and longer burning periods. Vegetation types are also altered in a changing climate. In turn, fires influence climate by the emissions to the atmosphere of aerosols and GHG, and by affecting the ability of biomass to sequester carbon.

Climate Variability (Short-Term Climate Change)

The documented link between open vegetation fires and climate variability associated with sea surface temperature anomalies and extended droughts is demonstrated by the most studied low-frequency climate cycle, the globally significant ENSO, shown to impact fires in South East Asia, Central and South America, and boreal regions of Eurasia and North America.[62,82,110] Regionally significant climate phenomena such as the Arctic Oscillation (e.g., Siberia),[111] Indian Ocean Dipole (IOD), Indonesia,[112] Atlantic Multidecadal Oscillation (e.g., Boston Mountains),[113] and Pacific Decadal Oscillation (e.g., Alaska)[114] have also been identified to affect fire occurrence (Figure 6). The synergistic impact of the large-scale and regional climatic phenomena can enhance fires, leading to exceptionally intensive biomass burning such as the 1997/1998 Indonesia fires, attributed to the combined strength of the El Nino and the IOD.[112] Observed interregional differences in fire patterns can also be attributed to changes in land use and population density, driven by humans. For example, a strongly nonlinear link between drought and fire emissions is demonstrated by comparing the fire carbon emissions in Indonesia during the moderate 2006 El Niño that are 30 times greater than those during the 2000 La Niña. This is due to a direct anthropogenic influence since ignitions are mostly anthropogenic more clearing occurs in drier years

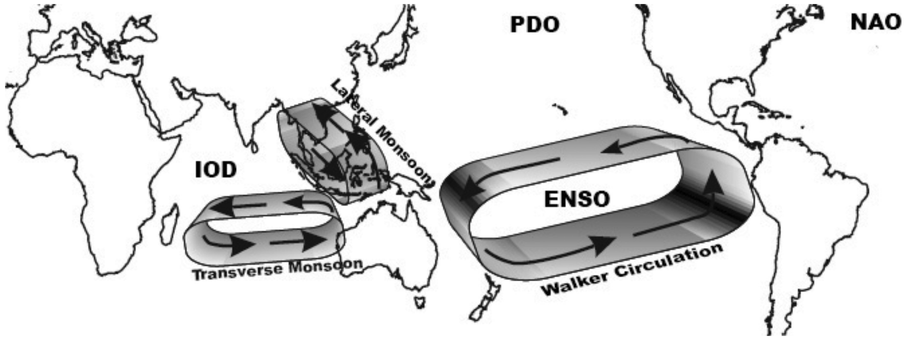

FIGURE 6. The principal atmospheric circulation patterns affecting tropical fires.

leading to greater forest loss rates and exposure of larger areas of peatland, becoming vulnerable to fire in the drought years.[115]

In addition to the fire behavior changes, the atmospheric fate of fire emissions can be influenced by changes to climatic phenomena that affect atmospheric transport. El Niño–induced meteorology resulted in enhanced transport of boreal forest fires emission from Siberia to Canada, and high North Atlantic Oscillation Index resulted in transport of emissions to higher latitudes over Europe.[116] An exceptional ozone episode during the 1997 ENSO and IOD events was associated with anomalous subsidence bringing ozone toward the surface causing an increase of tropospheric ozone column that was further affected by the fire emissions chemistry.[54] Forest fires in Siberia may have contributed to a rise in atmospheric CO_2 concentrations of greater than 2 ppm per year during 2002 and 2003.[117] A statistically significant relationship between interannual variability of Siberian forest fires and climate indices including summer temperatures and precipitation has been demonstrated.[111] Boreal forest fires occur annually at the onset of the tundra thaw when natural fires and those set by subsistence farming practices become uncontrolled. During warmer winters the thaw moves north, exposing a greater carbon reserve to liberation through fire. Permafrosts create a heat sink during summer months so that reduction in area of permafrost will result in heat being transferred to the atmosphere, and hence enhanced warming. Through this process, projections suggest that the Arctic may be a carbon source as early as the 2020s,[118] and Paleo evidence suggests that tundra fires are presently occurring at greater frequency than during the last 5,000 years.[119]

The examples demonstrate the complex relationship between fires and climate, both in terms of developing the conditions for fires to start and thrive and the subsequent impact the emissions have on climate. Some have suggested that a consequence of climate change will involve changes to natural variability and climate phenomena. For example, in a warmer stabilized climate, models suggest an increase in the amplitude of El Niño (although a change in frequency is more debatable).[120] In addition past climate change has been accompanied by changes in ENSO amplitudes suggesting the same may happen in a future warmer climate.[121] The strong correlations of fires with climate parameters, and the predicted changes in these parameters due to climate, also suggest significant future change of fires.

Long-Term Climate Change

Under climate change, warmer temperatures and precipitation changes are expected to be the main climate drivers for fires by changing the frequency and the intensity of fires.[122–125] A compilation of fire information between 1970 and 2002 for forests in the western United States indicates that wildland fire frequency and intensity may already be increasing.[123] Interannual variability of fire activity discussed previously is an indication of some of the behavior that could be exhibited under long-term climate change. The present level of understanding of the long-term climate change influence on biomass burning was recently summarized (Flannigan 2009) Q12

Projections, most of them based on atmospheric scenarios involving increasing CO_2 levels, suggest an increase in fire frequency under climate change. For example, a doubling of area burned along with a 50% increase in fire occurrence is foreseen in parts of the circumboreal by the end of this century.[125] For Canada and Alaska the average area burned per decade is expected to double by 2041–2050 (relative to 1991–2000) and increase on the order of 3.5–5.5 times by the last decade of the 21st century.[126] Recent projections suggest an increase in fire occurrence across Canada of 25% by 2030 and from 75% to 140% by the end of the 21st century.[127]

A 55% increase in the probability of extreme fire risk across Australia from grasses and forests by 2100 under a relatively low emission scenario of 621 ppm CO_2 has been projected.[128] Under a 2 X CO_2 climate a 5 °C increase in temperature and 20% decrease in precipitation for Western Canada has been projected, resulting in an increase in the Canadian Fire Weather Index of 20%.[129] Increases in the seasonal severity rating of 46% across Canada[130] and 10–15% across North America[131] have been projected using 2 X CO_2 scenarios. Additionally, longer fire seasons for Canada have been projected.[132,133] Under a changing climate the Nesterov fire danger index is predicted to increase by 2080, especially in southern Siberia.[134] Area burned in Canada has been projected to increase by 74–118% in a 3 X CO_2 climate scenario.[124]

A number of climate scenarios indicate shifts in the precipitation patterns (causing increased drought). For example a significant reduction in the area of the Amazon forest during the 21st century has been predicted, mainly as a result of increased fire disturbance associated with drought conditions.[135] The increases in extreme fire risk projected for Australia by 2100 were driven by climate warming and the associated reductions in relative humidity.[128]

Conversely, predicted increased precipitation in Eastern Canada has resulted in projections of decreased areas burned.[136] Land use changes in the Amazon are also expected to increase fire disturbance; future development in the Amazon is predicted to result in increased fire activity (22–123%).[137]

The initiation of fires through lightning may also be influenced by changing climate. Presently lightning initiates 35% of fires burned in the boreal forests of Canada, but is responsible for 85% area burned.[138] An increase in convection under a 2 X CO_2 climate could lead to an increase in lightning that would result in a 78% increase in area burned across the United States.[139] A projected 1.8-fold increase in lightning fire initiation by 2080–2089 relative to 1975–1985, would result in a 2.6-fold increase in boreal mixed wood forest area burned in central eastern Alberta, Canada.[140] However the relationship between lightning and convection (and climate) is rather speculative, and further robust observational lightning data are required in order to understand the role of lightning in initiating fire in the future.

Climate change impact on wildfire emissions of carbonaceous aerosol in the Western United States out to 2050 has been simulated[141] based on area burned[124] and focusing on wildfires in forest dominated ecosystems where the main control of fire activity is understood to be meteorology.[142] Mean summertime organic carbon over the western United States between 2046 and 2050 was projected to increase by 40% and elemental carbon by 18% relative to 1996–2005 with largest increases occurring in the northwest United States, colocated with increased fire activity. This would increase the fraction that carbonaceous aerosol comprises of fine aerosol over the western United States from 40% to 50% by 2050.[143]

Limitations

The present modeling of fire occurrence and impacts has a number of limitations to be addressed as the scientific understanding of the processes involved develops. Presently the quantity of fuel consumed is not accurately represented in models. Fuel loads and fire severity both influence fuel consumption. Increasing fire activity could lead to a decrease in the fire return time interval potentially resulting in a decrease in the age of trees and the fuel consumption per area burned. For example, an 18% reduction in the quantity of the fuel consumed in the western United States has been calculated, assuming no time for vegetation to recover between fires.[141]

Fire severity is influenced by climate change, with increased temperature and decreased moisture resulting in more severe fires. Fuel consumption by the wild fires in the Canadian boreal forest has been projected to increase by up to 18%.[144] The impact of fire severity in nonboreal forests remains unclear and the combined effect of fuel consumption and fire severity could amplify or suppress projected changes.[141]

Few projections take into account the effect of vegetation changes and human intervention (e.g., fire management and land use activities). For example, warming is projected to be greatest in the northern latitudes and decadal scale periods of warmer temperatures in northern Siberia have been linked to large-scale tree line changes in high-latitude boreal forests, with the tree lines migrating northwards during warmer periods.[145] The predicted movement of Siberian forests northward will increase the coverage of steppe ecosystems, becoming predominant by 2080.[134] However, permafrost is not predicted to thaw enough to support dark taiga forest. Fire danger is predicted to increase by 2080, mainly resulting from the accumulation of fuel loads when steppe replaces forests combined with more frequent fire weather and the resulting feedback of more wildfires creating grassland habitats that have a greater propensity to burn. Moisture changes in a 2 X CO_2 climate in Western Canada could result in expansion of aspen parkland northward at the expense of true boreal forest, and while species migration may not follow climate drivers directly, different fuel conditions may predominate under different future climates.[11] However fire itself could cause a species shift as more fires create younger forests dominated by successional species such as aspen.

POLICY PERSPECTIVES

Local Fire Management

Managing emissions from fires continues to be a contentious issue and requires significant resources from government, industry, and community, particularly as more land becomes settled and the urban-wildland interface is extended. Fire suppression, prescribed burning, forest thinning, and natural wildfires are some of the policies that have been employed to manage fires. The approaches used depend largely on the nature of the fire regime, and the land use activities that are affected.

Fire suppression is the complete prevention and extinguishing of any fire. The effectiveness of fire suppression in controlling fire activity is heavily debated and seems to be dependent on ecosystem type. The suggestion that fire suppression increases the probability of a catastrophic fire event is based on the accumulation of fuel that occurs under a fire suppression regime. Some ecosystems such as yellow pine forests have a long history of surface fires so that fire suppression policies have resulted in the exclusion of fire during the last century, the accumulation of fuel and the consequent occurrence of large crown fires.[146] However, in the boreal forests of Ontario, there is insufficient evidence to suggest that suppression of fire has significantly changed the fire cycle.[147]

Fire suppression depends on extinguishing small fires quickly (until, as discussed previously, fire load increases to the point where unsuccessful suppression results in a large numbers of escape fires) and hence has a narrow margin between success and failure.[133] Under a warming climate there is some suggestion that the ability of management agencies to deal with these increases in fire activity is limited (particularly if resources available to do so remain constant) so that a disproportionate number of fires may escape initial attack under a warmer climate, resulting in an increase in area burned that will be much greater than the corresponding increase in fire weather severity.[125]

Prescribed burning is the deliberate ignition of fires in specified and controlled areas, the main aim of which is to remove accumulated fuel. The effectiveness of prescribed burning in controlling fire is also heavily debated. For example, the prescribed burning model may have been inappropriately applied to the boreal forests of Canada, where crown fires are an inevitable consequence of the fuel structure and burning is not age dependent.[148] However, a number case studies point to the positive effect of prescribed burning on reducing the progression of wildfires in several ecosystems including pine forests of Florida,[149,150] Californian conifer forests,[151,152] California chaparral,[153] and eucalypt forest in southeastern Australia and southwestern Australia.[154] A model of vegetation dynamics and fire spread was used to determine the importance of suppression and prescribed burning on wildfire size in Mediterranean ecosystems and found that area burned was similar in the two fire management regimes, although the suppression of fires resulted in the dominance of large fires.[155] Another recent modeling study suggests that prescribed burns reduce the occurrence of severe wildfires that remove carbon-sequestering large trees in addition to the understory and thus reduce the overall carbon emissions.[156]

The effectiveness of any fire management policy is tested when fires occur during extreme weather events such as very strong winds, low relative humidity, and high temperatures. Fire intensity increases (nonlinearly) with decreasing fuel moisture and increasing wind speed, both of which are more variable than fuel characteristics. Hence when strong winds and low humidity are the drivers behind large fires, reduction in fuel amount is ineffective.[157,158] A significant fraction of global area burnt is the result of a very small number of very intensive wildfires and driven by extreme weather.[159]

A correlation between fire frequency and population suggests that fire suppression may not be responsible for the increasing destructiveness of Californian shrublands wildfires.[157] Again, these catastrophic brushland fires are often driven by extreme weather, particularly very high winds associated with the Santa Ana.[160] The correlation of fire frequency with population suggests that many of these fires result from human activity (either deliberate or unintentional). The urban interface continues to expand as a preference for the rural lifestyle and prices for suburban housing in large cities rises, so in the future not only will we see the influence of increased temperature (and hence extreme fire weather) on determining fire, we will see increased population at the urban interface compounding the risk of catastrophic wildfires. The policy implications of this lie in the management of the urban interface expansion and could include restrictions on the location of buildings and infrastructure as well as controls on materials and building designs and management of recreational areas.

A number of factors constrain prescribed burning programs including suitable weather for burning, adequate funding, landscape, conservation issues, and impact on air quality particularly for urban interface locations. Often the requirement to comply with air quality regulations is an important restriction to prescribed burning activity. In Australia the National Environment Protection Measure for PM10 includes an allowance for five exceedances per year to cater for high particle concentrations resulting from activities such as prescribed burning and natural dust events. However, at the urban interface in Sydney, 27% of area requires annual burning to reduce hazard,[161] potentially impacting air quality levels for more than five days per year.

In general prescribed burning places minimal emphasis on ecological considerations and in ecosystems with a history of low intensity surface fires, the risk to conservation should be negligible. However in ecosystems that experience large infrequent crown fires as part of the natural fire process this is not the case. There is a lack of information from long-term studies on the ecological effects of prescribed fire regimes.[158]

In savannas, where fire is an integral part of the ecosystem and therefore is essential for the maintenance of many plant and animal communities, the focus has ranged from zero intervention to complete suppression. Without fire management, fires ignited in the late dry season develop sufficient intensity to burn for many days without control across large areas often damaging fire sensitive plant communities. The present approach to fire management, applied particularly in the indigenous lands in Northern Australia, is to return to the management regimes practiced by the traditional owners prior to European intervention. In parts of Australia, the knowledge of these strategies remains with the elders who are now working closely with the fire agencies to implement them.[162] The management strategy is to undertake low intensity prescribed burning in appropriate fire resistant communities during the early dry season to establish barriers to the progress of high-intensity late season fires. This leads to both reduced GHG emission[163,164] and biodiversity protection.[165]

Global Policy

The complex interaction of fire, climate, and human activity and biome characteristics means that the isolated treatment of any of these factors in policy discussion is inherently flawed. Instead an integrated approach is required to understand the relationship fire has with these factors. In the Driver-Pressure-State-Impact-Response conceptual framework,[166] nonanthropogenic drivers for fire include ecosystem services and global carbon cycling. Poverty is a significant human driver, in particular the need for inexpensive land and food production that results in shifting land use practices. Policy directives may also contribute to these drivers for example policy to meet biofuel use targets. Pressures include emissions of GHG and aerosol and changes to biodiversity and biomes. Indicators of state are changes to land cover, albedo, radiative forcing, and reduction in air quality, all of which have been discussed throughout this article. Response includes local, regional, and global policies and incentives aimed at reducing the impact of fire.

The development of environmental policies that reduce emissions from biomass burning is challenging. Part of the challenge lies on the possibility to have reliable estimates of emissions from biomass burning. In addition, it is difficult to distinguish between emissions resulting from unwanted fires such as those associated with deforestation activities, undesirable naturally or anthropogenically initiated fires and fires that are considered important for ecosystem maintenance such as African and Australian savanna fires or prescribed burns for fire management. In the latter case it is still important to be able to estimate these emissions.

A number of international or global activities exist to promote cooperation and collaboration that may indirectly reduce the impacts of biomass burning emissions. Of these, the United Nations Framework Convention on Climate Change (UNFCCC), requires Annex 1 (i.e., industrialized) countries to include in their annual GHG inventory reports the emissions from biomass burning within the sectors of land use, land use change, and forestry (LULUCF) as well as agriculture. These inventories are subject annually to a review by a team of experts coordinated by the UNFCCC secretariat. It is important to note that, given the difficulty to distinguish between the human and the natural origin of emissions and removals from LULUCF, these GHG inventories include only the emissions and removals occurring on managed lands. In other words, the concept of managed land is used as a proxy for anthropogenic effect.

Analysis of the GHG inventories submitted to UNFCCC[1] shows that the emissions from biomass burning reported by Annex 1 countries in the last 10 years averaged about 575 Mt CO_2-eq./year (range 400–800 Mt CO_2-eq./year),[2] the vast majority from LULUCF. The highest emissions are reported by the United States, Canada, Australia, and Russia, and in some years equaled a large part of total country's fossil fuel emissions (up to 40–50% in Canada and Australia). For most countries, the majority of these emissions are due to forest wildfires, although in some case significant emissions are also reported for grasslands and croplands (e.g., Australia).

The UNFCCC also requires non–Annex 1 (developing) countries to report emissions from their land use sector (including biomass burning) in periodic National Communications.[3] Although the available data suggests a significant contribution from biomass burning to overall emissions in

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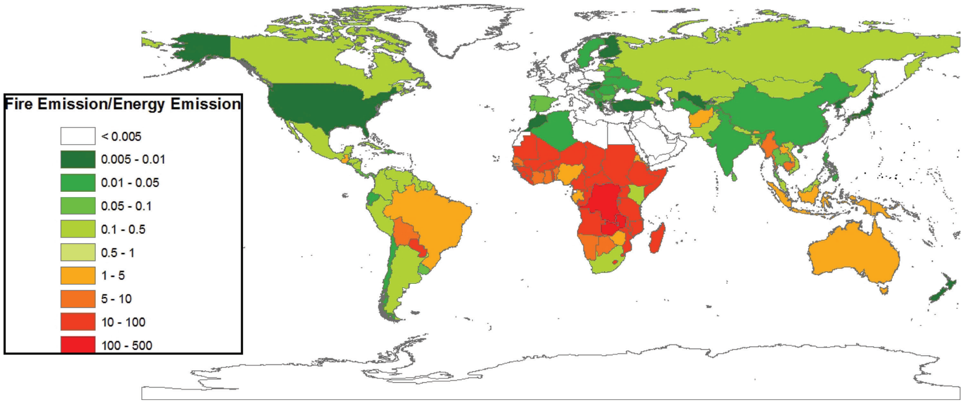

FIGURE 7. Ratio of national emission of carbon from biomass burning (from GFED2 database[82]) to emission of carbon from combustion of fossil fuels (determined from national energy statistics from the International Energy Agency database.[177] (Color figure available online).

developing countries, it is difficult to provide global estimates because many countries do not provide complete and updated information.

Other sources of information confirm that the relative contribution of biomass burning over total emissions is significantly higher in developing countries than in industrialized ones. For example, Figure 7 shows the estimated ratio of carbon emissions from fires to carbon emissions from fossil fuel use, without taking into account the uptake by previously burned vegetation that is regrowing. The highest ratios occur between 30° north and south of the equator particularly in developing nations where fossil fuel use is low. In central Africa where savanna fires are a dominant feature of the ecosystems, in southeast Asia, where clearing of rainforest for agriculture and timber production are major activities, and in South America where forest clearing and savanna burning are extensive, fires dominate all emission sources exceeding fossil fuel emissions by one or more orders of magnitude.

With respect to the policies aimed to reduce emissions from biomass burning, a distinction should be made between UNFCCC and the Kyoto Protocol. While the UNFCCC contains only a general commitment for reducing emissions, the Annex 1 countries that ratified the Kyoto Protocol accepted a legally binding emissions limitation commitment (i.e., an emission target). The accounting of emissions and removals from the LULUCF sector within the Kyoto Protocol, which contributes to reach the legally binding target, is mandatory for some activity (afforestation/reforestation and deforestation since 1990) and voluntary for other activities (forest management, cropland management, grazing land management, and revegetation). Given the quantitative importance of biomass burning emissions for several countries, the treatment of these emissions in the accounting (i.e., in the assessment of the compliance with the emission targets) always represented an important issue of debate in climate negotiations. In particular, the use of managed land as a proxy for anthropogenic effect, applied in the reporting of fire emissions to UNFCCC, is also used for accounting purposes during the first commitment period of the Kyoto Protocol (2008–2012). This means that if a country has voluntarily decided to account the emissions and removals from forest management under the Kyoto Protocol, any emission from fires occurring on managed forests should be accounted irrespective of its (often unknown) underlying cause. As the risk of large and uncontrollable emissions from fires in managed forests may be significant, the present approach has contributed to the decision of some Annex 1 country (e.g., Canada, Australia) to not account for forest management in the first commitment period of the Kyoto Protocol.

In the present negotiations for a post-2012 climate regime, there is strong interest in making the accounting of emissions and removals from forest management mandatory for all Annex 1 countries. Although the future LULUCF accounting rules are yet to be finalized, there is wide support for a new accounting approach that, through the concept of force majeure events,[4] would reduce the compliance risk with the overall emission limitation commitments (i.e., the risk that a country will not reach its overall emission target because of uncontrollable emissions from fires). This approach would help to extend the accounting of emissions and removals from forest management in all Annex 1 countries, and thus indirectly represents an incentive to increase the control over the emissions from biomass burning.

Furthermore, a similar approach may also be applied to the Reduced Emissions from Deforestation and Forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks (REDD+ mechanism), which will provide incentives to developing countries to reduce emissions and loss of forests. Given the importance of emissions associated with deforestation activities, the implementation of the REDD+ mechanism would represent an additional important incentive to reduce the emissions from biomass burning.

CONCLUSION

This work has provided a review of the present state of knowledge regarding the role of biomass burning in influencing climate, the role of climate in influencing biomass burning and the tools available to observe and predict biomass burning emissions. Policy and management practices that influence biomass burning emissions have also been briefly touched on. This review has clearly documented that biomass burning results in the emission of GHG and aerosol to the atmosphere and that in some instances these emissions can be as significant (or more significant than) emissions from industrial activity (e.g., 1997/1998 El Niño Indonesian peat fires[15]). This review has also demonstrated that under a changing climate, the frequency and intensity of fires is likely to increase (e.g., southeastern Australia).[168]

Reduction of the emission of biomass burning GHG and aerosol to the atmosphere faces a number of challenges. The first concerns the distinction between fires for ecosystem service delivery (e.g., maintenance of many plant and animal communities in savanna ecosystems) and fires that are deliberately lit to serve human purposes (e.g., land use change or fire management). Naturally lit fires can be intense sources of emissions, and while fire management activities such as controlled burning and fire suppression are aimed at reducing the severity and frequency of these burns, the present discussion has highlighted the absolute importance of the appropriate methods being used in different biomes.

The choice of fire management procedures should rely on a sound understanding of the fire history of the biome, and should have contingency for the occurrence of severe fire weather. Consequently the effectiveness of any fire management policy can only be gauged if the correct tools are available to assess metrics of success.

Similarly the control of emissions from deliberately lit fires can only be achieved by good advice based on good data. In particular for a developing nation to participate in global emission reduction schemes they need to be able to account for their emissions. It is the role of the scientific community to work towards the development and provision of the tools required to do this.

The provision of good data on which to base sound advice, policy and projections can be seen as a second significant challenge. The actions required to develop the tools and data required to provide advice for fire management and emission reduction include the following:

- Improvement in the spatial and temporal resolution of burned area products derived from satellite observations so that smaller fires of shorter duration can be accurately mapped. This may be achieved by a hybrid of fire counts and burned area products from polar satellites and fire activity from geostationary satellites.
- Routine use of new algorithms that quantify fire radiative power from satellite data will reduce uncertainties in emission estimates attributable to uncertainties in fuel loads and combustion efficiency.
- Verification and validation of satellite products and the understanding of inconsistencies between products from different satellites and between biogeochemical models in the determination of emission estimates are required. Quantifying the seasonality of EFs is a research priority. Verification of a bottom-up inventory model structure and parameters will lend confidence to the model predictions; however, independent validation with tools such as inverse modeling is required to consolidate emission estimates.

- The incorporation of fire modules in Earth System Models will enhance our understanding of the impact of climate on fires and vice versa. Such models will need to represent the physical fire processes as well as the influence of anthropogenic ignitions, fire suppression policies and resources, and degrees of fire management.

The third significant challenge lies in the policies and actions to reduce biomass burning emissions. For example, banning agricultural waste burning and intentional land clearing burning completely could greatly reduce emissions under the condition that appropriate alternative methods are applied. While in several regions laws already exist against such practices, an improved control system and implementation of stronger legal actions would clearly have large benefits. However, such actions will be ineffective in the case where livelihoods and even survival are dependent on these practices. At the international level, we have discussed how possible amendments to LULUCF rules under the Kyoto Protocol, presently under negotiation for a post-2012 climate mitigation agreement, have the potential to promote a broader accounting of emissions and removals from forests; this in turn, would represent an important incentive to control the emissions from biomass burning.

Unintentional forest fires will be difficult to avoid completely, but setting requirements on technical installations or other causes to ignition (train breaks, broken glass in litter, power installations) will reduce the frequency of fires. A ban on specific installations proven to have a high risk of causing an ignition could be considered. In addition management of the urban interface expansion requires particular consideration and could include restrictions on the location of buildings and infrastructure as well as controls on materials and building designs.

The science behind naturally lit fires and the ability to project biomass burning activity is important, particularly given the likelihood of changing climate increasing the severity and frequency of wildfires. The dependence of wildfires on socioeconomic drivers in Africa has been demonstrated,[169] hence it will also be important to understand the relationship between fire and socioeconomic parameters such as population density, land ownership structures, and economic indicators in determining how wildfires can be used as management tools. This will require an integrated assessment approach to the problem.

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NOTES

1. See http://unfccc.int/national_reports/annex_i_ghg_inventories/items/2715.php **Q13**

Q14 2. This estimate is derived from CRF tables LULUCF 5(V) (biomass burning, including both wildfires and controlled burning) and Agriculture 4.E (prescribed burning of savannas). Several countries did not explicitly included CO_2 emissions from biomass burning in table 5(V); in these cases, we indirectly derived CO_2 emissions from CH_4 and N_2O reported emissions, using default factors from IPCC Good Practice Guidance for LULUCF.[167] It should be noted that not all Annex 1 countries reported complete information on emissions from biomass burning on managed lands.

3. See http: //unfccc.int/ national_reports/ non-annex_i_natcom/ items/2716.php **Q15**

4. According to the draft negotiation document FCCC/KP/AWG/2010/CRP.3, "Force majeure means extraordinary events or circumstances, defined as those events or circumstances whose occurrence or severity was beyond the control of, and not materially influenced by, a Party." A possible threshold for the purposes of applying the definition of force majeure (e.g., X% of total national emissions included in the base year) is presently under negotiation. **Q16**

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