

Fire influences on atmospheric composition, air quality, and climate

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Abstract

Fires impact atmospheric composition through their emissions, which range from long-lived gases to short-lived gases and aerosols. Effects are typically larger in the tropics and boreal regions, but can also be substantial in highly populated areas in the northern mid-latitudes. In all regions, fire can impact air quality and health. Similarly, its effect on large-scale atmospheric processes, including regional and global atmospheric chemistry and climate forcing, can be substantial, but this remains largely unexplored. The impacts are primarily realised in the boundary layer and lower free troposphere, but can also be

noticeable in upper troposphere/lower stratosphere (UT/LS) region, for the most intense fires. In this review, we summarise the recent literature on findings related to fire impact on atmospheric composition, air quality, and climate. We explore both observational and modelling approaches, and present information on key regions and on the globe as a whole. We also discuss the current and future directions in this area of research, focusing on the major advances in emissions estimates, the emerging efforts to include fire as a component in Earth system modelling, and the use of modelling to assess health impacts of fire emissions.

Introduction

Fire is a central component of the Earth system [1,2]. There are several key linkages between fire, the atmosphere, and the biosphere, with implications for climate change, ecosystems, human health, and the economy. Forest fire activity is strongly affected by climate change, since temperature, humidity, and precipitation can affect the flammability of vegetation [3,4], and since vegetation itself undergoes changes driven by climate change. Furthermore, fire activity depends on the ignition sources available in a region, which can be natural (lightning) or anthropogenic (accidental or deliberate) [4], with the natural sources potentially influenced by climate change as well.

Fire activity has changed drastically in the past, and is expected to change in the future. Specifically, it has been suggested that from the preindustrial to the present-day, fire activity increased until 1950 and subsequently decreased due to anthropogenic management [5], while in the future it will potentially increase

due to the climate warming expected [5,6,7]. At the same time, fire activity shows large interannual variations both on global and on regional scales [8]. The atmosphere is affected strongly by these changes in fire activity [9] through large amounts of emissions that can affect pollution levels, atmospheric chemistry, and climate.

There are both gaseous and aerosol emissions from fires and associated biomass burning. Carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane volatile organic compounds (NMVOCs) are the most important emitted gases, and black carbon (BC) and organic carbon (OC) are the most important aerosol species [10,11,12]. CO_2 emissions can have important implications for CO_2 concentrations and understanding the carbon cycle, but do not directly affect atmospheric chemistry or contribute to air quality degradation. Other carbonaceous emissions (BC, OC, CO, NMVOCs, and methane (CH_4), for which biomass burning is only a minor source) and NO_x can be important for both air pollution/chemistry and climate change. NO_x , NMVOCs, CO, and methane are important precursors of tropospheric ozone, which is a secondary pollutant and is not directly emitted by fires [9,10]. Such strong effects have been demonstrated in measurement and modelling studies, on scales ranging from local to global, but significant uncertainty still remains. In this paper, we provide a review of the current understanding of such effects, focusing on the recent literature. We examine the impacts of fire emissions on the abundances of gases and aerosols, and continue with a section on related radiative forcing and climate effects. Subsequently, we provide a critical discussion on future directions that will lead to better understanding of fire

effects on atmospheric composition, air quality, and climate, with an emphasis on improved emissions estimates, emerging integrated modelling, and understanding of implications for human health.

Effects on atmospheric composition

Emissions estimates

In an atmospheric composition context, the starting point for biomass-burning studies at large scale is to estimate emissions for different species. Satellite observations are the only practical means of estimating biomass-burning emissions at a global scale in a consistent way. There are currently two approaches to doing so. The first is to estimate total fuel consumption as the product of the area burned and the fuel consumed per unit area. This approach is used for the series of Global Fire Emissions Database (GFED) products [12], Fire Inventory from NCAR (FINN) [13] and, for particulate emissions, the Fire Locating and Modeling of Burning Emissions inventory (FLAMBE) [14].

The other approach is to infer fuel consumption from the Fire Radiative Power (FRP) determined from thermal infrared measurements. The Global Fire Assimilation System (GFAS) [15] and Quick Fire Emissions Database (QFED) [16] both use this approach. FRP-based estimates can be made in near-real time because they use thermal infrared signatures directly, rather than an area-burned estimate based on the difference in burn scar signature before and after a fire. This makes FRP-based approaches better suited to real time air quality forecasting systems such as the EU Monitoring Atmospheric Composition and Climate (MACC) forecasting system and the NASA GEOS-5 Aerosol Modeling and

Data Assimilation System. FRP is converted to dry matter fuel consumption via biome-specific conversion factors. Emissions estimates for key species, namely CO₂, CO, methane, NO_x, OC and BC from GFEDv3, FINNv1 and GFAS, and for total particulate matter (TPM) from the above databases and from FLAMBE are summarized in Table 1 to provide a sense, globally, of the spread across estimates.

Gases

In the latest (Fifth) Assessment Report of the Intergovernmental Panel for Climate Change (IPCC AR5), it is stated that no estimate for the role of fire in driving long-term (e.g. Holocene) CO₂ and climate changes can be given because fire is a newly studied component of carbon cycle studies [18]. A growing body of work, however, indicates an important role. Liu et al. [19] suggest the fires are one of the important atmospheric CO₂ sources and contribute substantially to the global greenhouse effect. On interannual timescales, recent analysis [20] suggested that fires can be a significant driver of atmospheric CO₂ variability, along with the influences of temperature and drought on net ecosystem exchange.

Non-CO₂ effects of fires are also very important. To obtain emissions of different constituents for use in atmospheric modelling, emission factors are used. These represent the amount of the chemical species released per mass of biomass burned, and are typically obtained from measurement campaigns in biomass burning regions [11,21,22]. The largest gaseous non-CO₂ fire emissions are those of CO, which are a result of incomplete combustion, especially from smouldering

peat fires [12]. Amongst the short-lived constituents emitted from fires, CO has the largest potential to impact atmospheric composition on large geographical scales (hemispheric, or even global), due to its comparatively long lifetime of a few months. Mao et al. [23] found that the global CO burden increases linearly with step-wise increases in gaseous biomass burning emissions. Using a nudged global composition-climate model in conjunction with observations, the interannual variability of the global CO burden has been shown to be almost entirely driven by biomass burning emissions by Voulgarakis et al. [24,9], overshadowing the influence of other factors such as direct anthropogenic emissions and meteorology. The “hot-spots” of CO interannual variability [9] were found to be the Maritime Continent and South America, with strong variability also over Siberia and Canada. The interannual variations in fire-generated CO are closely linked to El Niño Southern Oscillation (ENSO) climate variability, which affects drought conditions primarily in Equatorial Asia and South America and subsequently fire activity [12] with both regional and global impacts. Along the same lines, observational analysis [25] showed that fires drive the interannual variability of tropical upper tropospheric CO, with the Maritime Continent being the primary contributor.

The effect of ENSO on tropospheric CO via fires is also realised in regions far from the tropics. A chemistry-transport model (CTM) study [26] found that fire emissions drive 66-93% of Arctic CO interannual variability, with ENSO being a major driver. They suggest that high latitude winter/spring precipitation is influenced by ENSO, which drives fluctuations in fire activity, and, therefore, fire emissions and atmospheric CO. This effect, they claim, could become more

severe in the future, as boreal forest regions become hotter and drier. Without examining ENSO influences, Strode et al. [27] discuss how biomass burning strongly impacts the interannual variability of CO in northern mid-latitudes, which affects the ability to detect anthropogenically-driven trends in CO.

Fire also has significant impacts on regional CO pollution levels. For Southeast Asia, Aouizerats et al. [28] found that during the fire season of 2006 (El Niño year), CO concentrations in the station of Bukit Kototabang (Sumatra) were elevated above 250 ppb in several occasions, with the most pronounced enhancements (>1000 ppb) found in October. They demonstrate that these large enhancements can be simulated successfully with a regional meteorology/chemistry model using the GFED3 emissions dataset, while the smaller increases due to smaller fires in earlier months cannot be fully captured. Reddington et al. [29] used back-trajectories and global modelling to examine the contributions from fires to surface CO over Singapore between 2004-2007, and found that the highest amount of fire-produced CO transported to Singapore occurs in September and October, with the strongest contribution coming from fires in southern Sumatra and a secondary contribution from fires in Indonesian Borneo. They also found substantial seasonal and interannual variability in those transport patterns. Using global modelling, Marlier et al. [30] examined six tropical stations in Equatorial Asia, Africa and South America, and found that including fire emissions from GFED3 improved the ability of the model to capture observed CO in most stations.

Other important gaseous species emitted from fires mainly include NO_x and NMVOCs [10,11,22], with their atmospheric effects being less thoroughly examined in the literature, but with evidence that they can be important (for example it was suggested that fires have a widespread impact on atmospheric abundances of benzene, an important NMVOC pollutant [22]). These fire-driven NO_x and NMVOC increases, along with the earlier mentioned CO increases, can lead to significant tropospheric ozone production, since all the above-mentioned species are ozone precursors. Jaffe and Wigder [31] thoroughly examined ozone production from fires in the literature, and particularly focused on observed enhancement ratios of ozone to CO ($d\text{O}_3/d\text{CO}$) as indicative of ozone production. They found $d\text{O}_3/d\text{CO}$ to range from -0.1 to 0.9, due to factors such as fire emissions, efficiency of combustion, chemical and photochemical reactions, aerosol effects on chemistry and radiation, and local and downwind meteorological patterns. However, other recent studies suggest that positive $d\text{O}_3/d\text{CO}$ is not always an indicator of an ozone producing region [32,33], especially in cases where there is substantial CO loss in a plume due to intense production of OH from ozone. Parrington et al. [34,35] discussed in detail ozone production in fire plumes in North America and the northern Atlantic. Their analysis suggests that plumes younger than 4 days feature low ozone production efficiencies that increase for older plumes, associating this feature with the relatively quick reduction of aerosol loading with plume age. Aerosols attenuate shortwave radiation and thus slow down the photolysis of NO_2 , which is essential for ozone production in the troposphere, while also they provide surfaces for heterogeneous uptake and loss of ozone and NO_y (collective name

for oxidized forms of nitrogen in the atmosphere, which facilitate ozone production) [36].

Global chemistry-climate model analysis [23] found that global tropospheric ozone production and burden linearly increase with fire emissions, as a result of the high NMVOC/NO_x ratio in such emissions. They showed that co-emission of trace gases and aerosols from present-day biomass burning increases the global tropospheric ozone burden by 5.1%. Biomass burning aerosols actually drive decreases in global ozone burden in their model, primarily due to heterogeneous processes, and not due to photolysis effects, which are not important globally, but are potentially important regionally. In terms of interannual variability, Voulgarakis et al. [9] suggested that fire emissions had little influence on global variations of tropospheric ozone, due to global ozone being a well-buffered quantity in atmospheric models.

The effect of fire emissions on regional ozone pollution levels can be significant. A series of studies from the western US provide a good illustration. Work using a statistical model along with the WRF-Chem regional weather/chemistry model demonstrated the large influence of fires on ozone production in the Western US, highlighting the important role of peroxy-acetyl nitrate (PAN, a reservoir of NO_x) in this process [37]. In one case in June 2008, up to a 60 ppbv increase in Reno, Nevada resulted from fires in California. Similarly, Singh et al. [38] examined the summer of 2008 and found that the highest ozone mixing ratios in Los Angeles (170 ppbv) were measured in a case where biomass burning influences were strong. Observational analysis by Wigder et al. [39] from a ground station in

Oregon found significant positive $\Delta O_3/\Delta CO$ ratios in plumes originating from wildfires in the western US and Canada, especially in cases where the plumes were confined to the boundary layer.

Still in the northern mid-latitudes (Mediterranean), Hodnebrog et al. [40] examined the impact of the large fires in Greece in the summer of 2007 and showed that they may have impacted ozone pollution levels by up to 18 ppbv. Over Portugal, simulations of ozone levels improved by 15% when accounting for fire emissions [41]. Surface and satellite observations along with backward trajectory analysis [42] showed that 56% of the acute pollution events with enhanced ozone at a surface station in Nepal were likely to be affected by emissions from open fires along the Himalayan foothills, the Indian Subcontinent and the Northern Indo-Gangetic Plain. In subtropical Taiwan, a study has calculated higher ozone by 8 ppbv in March in air masses that have passed over fire regions in the Mekong [43]. Closer to the equator, it has been found that high ozone episodes in Malaysia are associated with transport of biomass burning plumes from Sumatra [44]. However, on average, Marlier et al. [30] found no substantial improvements in the performance of a global model against observations in terms of tropical surface ozone when including fire emissions in the model.

Apart from ozone, biomass burning emissions can affect other important constituents involved in atmospheric chemistry processes, such as the hydroxyl radical (OH), which is the most important oxidant in the troposphere.

Voulgarakis et al. [9] showed that most of the interannual variability in global

mean OH concentrations is driven by biomass burning, as a result of the strong global CO fluctuations due to ENSO-modulated fire emissions (CO consumes OH during its oxidation). El Niño and the associated intense burning in the tropics (and, to some extent, the extratropics), can also lead to increased methane levels, both due to anomalous methane emissions and due to the longer methane lifetime resulting from increased global CO levels (CO consumes OH that could have otherwise contributed to methane loss) [45]. However, this effect on methane is significant only in very strong El Niño events (such as that of 1997-1998) and, in general, fire contributions are estimated to have a relatively small impact on the methane budget [46].

Aerosols

Fires are also responsible for emissions of large amounts of aerosol constituents, especially BC and OC [11,12]. Global-scale studies focusing on the large-scale effects of fires on aerosol abundances have been surprisingly sparse. The recent model analysis by Jacobson [47] which focused on climate effects, found that biomass burning increased global mean absorbing aerosol optical depth (AAOD) by ~55% and total aerosol optical depths (AOD) by ~15%. When it comes to interannual variability, recently Voulgarakis et al. [9] was suggested that fires are a strong driver of the global aerosol burden, but only when excluding the heavy components of dust and sea-salt from the calculation. ENSO has again been suggested as an important influence on this variability, as it was also earlier discussed by Ji and Stocker [48] who mainly focused on the tropical aerosol index.

There has been a much larger number of studies on regional effects of fires on aerosols. In recent years, there has been substantial focus on the tropics. For the Brazilian Amazon, using surface in-situ measurements it was found [49] that concentrations of submicron aerosols reached $100 \mu\text{g m}^{-3}$ during biomass burning events in September/October 2012, with organic aerosols largely dominating the aerosol mass. A similar finding about the dominance of organic particles in this environment was also demonstrated by Atraxo et al. [50]. Similarly, in Southeast Asia, Lin et al. [51] found that sites that are heavily impacted by biomass burning experience elevated fine particle concentrations (with particles with diameters less than $2.5 \mu\text{m}$, namely $\text{PM}_{2.5}$, exceeding $45 \mu\text{g m}^{-3}$ on average), dominated by organic mass enhancements. In Singapore, it has been suggested [29] that fire emissions from Indonesia account for drastic enhancements of $\text{PM}_{2.5}$ pollution, as was also the case for CO. More recently, regional climate modelling revealed that Indonesian fires contributed to 17 days exceeding $50 \mu\text{g m}^{-3}$ concentrations of $\text{PM}_{2.5}$ in the July-October period of 2006 in Singapore [52]. Using global modelling, but focusing on the tropics, Marlier et al. [30] found that a model's ability to capture aerosol optical depths measured from AeroNet in all land tropical regions (Equatorial Asia, Africa, South America) improved drastically when including fire emissions in the simulations, in contrast to what happened with ozone, whose abundances are more buffered by other processes.

Substantial contributions from fires to atmospheric aerosol abundances have also been suggested for the extratropics. In the southwestern and western US, fires are a common reason behind intense pollution episodes; for example,

Zauscher et al. [53] showed that in October 2007 fires led to the concentrations of fine (<400 nm) particles reaching up to $148 \mu\text{g m}^{-3}$ in San Diego. In Oregon, an observational study found that fires lead to sizeable aerosol enhancements, and simultaneous analysis of $\Delta\text{PM}_{10}/\Delta\text{CO}$ ratios suggested significant secondary production in the biomass burning plumes that were less than 2 days old [39]. Using receptor models, which are common tools in air quality studies, Gibson et al. [54] quantified that the median boreal fire contribution to surface $\text{PM}_{2.5}$ in Halifax, Canada during summer 2011 was $0.14 \mu\text{g m}^{-3}$. Focusing on interannual timescales, Spracklen et al. [55] had earlier shown that western US organic aerosol variability is mainly driven by fires. Yue et al. [56], using a regression-based fire algorithm in conjunction with a CTM, estimated future impacts of fires on western US aerosols and found that changes in fire emissions may increase summertime surface OC by 46-70% and BC by 20-27% by mid-21st century relative to the present day, with even higher increases found for extreme episodes.

In Europe, fire contributions to aerosol pollution are more prominent in the Mediterranean basin in the summer. Bougiatioti et al. [57] found that biomass burning can contribute almost half of the organic aerosol mass at the island of Crete during periods with significant fire influence, and stress the importance of fires that occur remotely, in other parts of Greece and the Mediterranean in general. Strong increases (by 40-50% on average) of aerosol concentrations were found in Athens, Greece as a result of large fires in Russia and Ukraine in August 2010 [58]. Similarly to the eastern Mediterranean, fires have been shown to have sizeable effects in southwestern Europe. As was the case for ozone,

Martins et al. [41] showed that simulations of PM₁₀ levels in Portugal improved by 20% when accounting for fire emissions. For Spain, it has been found that biomass burning is responsible for about 20% of organic carbon levels in PM₁₀, PM_{2.5}, and PM₁ on an annual basis [59]. Studies have shown that biomass burning can have substantial contributions even in the north of Europe. A particularly prominent example is the fire-driven air pollution episode of summer 2010 in western Russia, which affected not only Russia itself, but also other parts of northern Europe [60], and even southern Europe [58], as mentioned earlier. For a boreal forest in Hyytiälä, Finland, using two independent analytical methods and three separate statistical methods, Corrigan et al. [61] showed that biomass burning is responsible for 25% of submicron organic aerosols in the area, especially in the relatively warm and dry months of summer.

In midlatitude Asia, the contribution of fires to aerosol pollution can also be significant, though less so compared to parts of North America and Europe. As was the case for ozone, Putero et al. [42] showed that BC levels in Nepal can be strongly impacted by open vegetation fires in the broader region. Further north, in the Arctic, fires have been shown to be a major contributor to BC and OC increases way above the regional background levels, with important implications for radiative forcing [62,63].

The Southern Hemisphere midlatitudes are exposed to less biomass burning pollution, due to the lower fraction of land mass compared to the Northern Hemisphere. However, due to the generally low levels of background pollution,

fire events can stand out as very important for regional aerosol pollution extremes e.g. in Australia [64].

Effects on UT/LS composition

The most energetic fires can inject smoke directly into the upper troposphere, and are referred to as pyroconvective plumes. They were discovered in the late 1990s over northwestern Canada, and are routinely detected over North America, Russia and Australia [65], where the combination of high fuel loads and strong synoptic disturbances provide conditions necessary for explosive fires and high altitude injection. Emissions from tropical biomass burning can reach high altitudes, but to the best of our knowledge this occurs mainly from horizontal advection into regions of deep convection rather than direct UT/LS injection [66].

Pyroconvective events are rare. Sofiev et al. [67] estimated that globally 90% of emissions were released below 3km. For 2004-2005 over North America, it was estimated that 8% of smoke plumes reached more than 2.5 km above the boundary layer [68]; only a small number of these are lofted directly to the upper troposphere. Strobe et al. [27] indeed found that the influence on tropospheric CO due to biomass burning decreases with height, being smaller at 500hPa than at the surface.

However, pyroconvective plumes are injected directly into the geostrophic flow and drier air, they are longer-lived, and can be transported thousands of kilometres. The plumes can remain intact as they cross the tropopause into the

lower stratosphere. An important recent example was the devastating 2009 Black Saturday firestorm in southeast Australia. Emissions were injected into upper troposphere over only a 4-6-hour period, but the plume's impact persisted for months. The plume was detected in the lower stratosphere three weeks after the initial emissions pulse, standing out over Africa from background levels of CO from Aura MLS [69], aerosol-sensitive radiances from Odin-OSIRIS [70], and HCN from Envisat-MIPAS [71]. The aerosol signature of the fires persisted until July 2009 in CALIOP scattering ratio measurements, ranking in strength between the small Kasatochi and Sarychev volcanic eruptions [72]. Pyroconvective plumes are likely a secondary source of pollutants in the stratosphere relative to volcanic eruptions, although a systematic comparison of their contribution has not been done with a full complexity composition-climate model. Their impact could also become a greater concern in future climates [73] with higher fire danger [7].

Effects on radiative forcing and climate

Fires can impact radiative forcing (RF) and climate through a variety of interactions that can involve both the atmosphere and the land surface [1]. Here, we will not focus on the latter (effects on non-fire vegetation carbon fluxes, albedo, transpiration), but will discuss in more detail the radiation and climate impacts through emissions of key constituents. Air pollution and climate are linked through a variety of interactions, in both directions: a) changes in temperature, humidity, rainfall, wind patterns, and radiation affecting the chemistry, microphysics and transport of pollutants (climate affecting pollution),

and, b) in turn, pollutants directly (in the case of greenhouse gases and aerosols) or indirectly (in the case of constituents impacting greenhouse gases and aerosols) exerting radiative forcing and subsequently impacting temperatures, circulation, and the hydrological cycle (pollution affecting climate) [74,75]. The latter direction (b) is of immediate relevance to the topic of this review.

There has been a range of localised and regional studies investigating radiative effects of fire emissions, especially of aerosols. Observations revealed a dramatic top-of-the-atmosphere (TOA) radiative effect (up to -65 Wm^{-2} on average) from aerosols emitted in the August 2010 Russian wildfires [76]. The average TOA effect of major outbreaks of fires in various parts of Asia in spring 2008 was estimated to be -12 Wm^{-2} by using air quality and radiative transfer modelling [77]. In the tropics, using satellite information and radiative transfer modelling, the direct radiative impact of Amazonian biomass burning aerosols was estimated to be -5.6 Wm^{-2} on average over a period of 10 years [78]. The latter study also mentions that locally and for high aerosol loadings, this effect reached 20 Wm^{-2} .

The effect of biomass burning aerosols on clouds, which, in turn, affect radiation and climate, has been a topic of debate. Koren et al. [79] discussed two different regimes of aerosol-cloud interactions over the Amazon. They suggest that low-aerosol conditions favour a rapid increase of cloud fraction as a function of aerosol loading due to microphysical effects, and high-aerosol conditions feature cloud decreases with aerosol loading, due to the atmospheric stabilisation by semi-direct effects of smoke particles (the latter has recently also been observed

as the major mechanism in tropical Africa [80]). Recent observational evidence has further confirmed this theory [81]. Apart from the above-mentioned effects, however, studies have also highlighted the impacts of aerosols on heating gradients and circulation, which can potentially be even more important [82,83].

On a global scale, little systematic work has been pursued to estimate RF from fire emissions. The only component of fire-related RF for which the latest IPCC report [74] provides an estimate is that of aerosols, and even for that the estimate is very uncertain ($\pm 0.20 \text{ Wm}^{-2}$ for preindustrial to present-day RF). The report also notes that this relatively small mean aerosol RF is a consequence of rather strong forcings of opposite signs by BC (positive) and OC (negative). We also stress that regional effects of biomass burning aerosols can be much larger than their global impacts, given the short aerosol lifetimes. Fire-generated (from precursors such as CO, NMVOCs, NO_x , and methane) tropospheric ozone and CO_2 RF estimates are not provided by the IPCC report, because fire has not been included as a component in global climate modelling efforts so far [18].

The only systematic study to date of the global radiative effect and preindustrial-to-present-day RF from a broad spectrum of effects from wildfires has been published by Ward et al. [84]. The authors used a land-surface model to estimate preindustrial, present-day, and future fire emissions, and subsequently fed these emissions to an atmospheric model to calculate RF. They estimated that preindustrial fires were responsible for a radiative effect of -1 Wm^{-2} with respect to a preindustrial climate without fires, with the largest contribution (-1.6 Wm^{-2}) resulting from aerosol indirect effects (AIE) through cloud

increases. The second most important component is that of CO₂, which results in a radiative effect +0.83 Wm⁻². The fire impact between 1850-2000 was also dominated by AIE, which caused a RF of +0.6 W m⁻². However, that is not caused by substantial changes in fire-emitted aerosols, but by increases in anthropogenic aerosols, which caused the cooling potential of fire aerosols to decrease. This effect was discussed more recently [85], with a broader perspective on all natural aerosol radiative effects. Between 1850 and 2100, Ward et al. estimated a RF of about +0.2 Wm⁻², with the aerosol direct effect (ADE) being key, but also with a large uncertainty depending on the future climate scenario influencing fire activity [84]. A variety of the factors involved in the modelling presented by that study (fire parameterisations, treatment of aerosols and AIE, OH representation which would affect ozone and methane RF) are heavily model-dependent, and therefore it is important to pursue further model studies of this kind.

The later study by Jacobson [47] performed shorter (20-year) transient global model simulations and found that total biomass burning may be causing a net global warming of 0.4 K (~1 K in the Arctic), because the warming effects (cloud and aerosol absorption; semi-direct) outweigh negative effects (ADE and AIE). However, both because that study is for a short, transient period, and because it included anthropogenic biomass burning as well in the calculations, it is not directly comparable to the study by Ward et al. [84]. Mao et al. [23], who used present-day global simulations, found that the global radiative effect from fire emissions due to aerosols and short-lived gases varies nonlinearly with biomass burning strength. They estimated a present-day net radiative effect of -0.19 Wm⁻².

² from such emissions, dominated by ADE and AIE, and compensated by methane increases (due to CO increases and OH decreases) and methane-induced increases in ozone and stratospheric water vapour. This changes to a positive effect when fire emissions are increased by 5 times above their present-day levels. The figure is much smaller for aerosols and substantially larger for methane compared to what Ward et al. [84] found for those radiative effects in a preindustrial atmosphere, which again highlights the importance for further studies on this topic.

It has also been suggested that fire emissions can have effects on large-scale circulation. Specifically, a modelling study suggested that the Hadley Cell circulation can be weakened due to the heating of the atmosphere and cooling of the surface that smoke aerosols cause in the tropics, with large precipitation reductions near the Equator offset by smaller increases north and south of it [86]. The area of study of fire effects on circulation and precipitation on large scales is very much at its infancy, and requires a lot more investigation in future research.

Future directions

Improvements in emissions

Aside from the TPM estimates, general consistency across global emission estimates in Table 1 can obscure larger differences regionally and over shorter periods. For the Black Saturday fires in Australia described above, it was found [87] that GFEDv3 estimates were at least a factor of two greater than FINN v1

estimates for all emitted species, and that both estimates were likely too low by at least a factor of 50% when their burned area was compared to more detailed, ground-truth, surveys. Zhang et al. [88] found that over the US their mid-infrared GOES-based FRP estimates of fuel consumption were higher than GFED3.1 by a factor of 1.2-3.3 for 1997-2010. Differences or biases in emissions can translate into large spread in modelled composition and discrepancies with trace gas and aerosol measurements. Globally, it has been required [15] that GFAS OC and BC estimates be scaled upward by a factor of 3.4 when input into the MACC system to obtain reasonable agreement with MODIS AOD retrievals, suggesting that the bias was aerosol-specific, given reasonable agreement with several trace gas species. Similarly large sensitivity to emission estimates, and discrepancies with composition measurements were recently found for the Moscow peat fires of 2010 [89], over the Mekong region from 2004-2009 [29], and northern sub-Saharan Africa [90].

The accuracy of burned area estimates will be limited by the sampling frequency and spatial resolution of the instruments from which they are derived. The MODIS instruments on board Aqua and Terra, for example, operate in a low-earth, polar orbit, which provides higher spatial resolution but limited sampling coverage. Because each instrument has a twice-a-day sampling frequency, fires can be missed, especially at lower latitudes because of the swath path [13]. Accounting for these gaps is difficult and currently somewhat add-hoc, as is accounting for possible diurnal biases when using data from both MODIS instruments, although statistical techniques have recently been explored to that end [91]. Emissions estimates will ultimately continue to benefit from improved

fire detection using instruments on board geostationary satellites such as GOES, Meteosat and MTSAT for combined near-global coverage [92], and with the combination of instruments such as SEVERI with instruments such as MODIS onboard polar orbiting satellites [93] and instruments with higher spatial resolution and coverage such as VIIRS [94] and the anticipated SLSTR [95]. Conversely, there is value in re-analysing older satellite data for the purpose of improving long-term estimates, as was done in [96] over Kalimantan, Indonesia using AVHRR data from 1980-2000. More use could also be done in comparing satellite-based estimates of fire characteristics to those from fire-fighting agencies when they exist, particularly in validating emissions from smaller fires and with higher-temporal variability [97,30].

For FRP-based estimates, further studies of the dependence of combustion rate on fuel condition will be helpful [88], as will further uncertainty characterization [98]. The fuel consumption database of van Leeuwen et al. [99] is an important resource for validating modelling fuel consumption across different biomes and under different fuel conditions. Emissions factor estimates will also benefit from further measurement [87] and characterization of biome-specific emission factors for different

constituents [100] (



Figure 1). The modelled fate of these emissions will benefit from improved injection height models and validation against observations [101], with a first-order goal to distinguish between smoke released into the boundary layer from that injected into the free troposphere.

Emerging integrated modelling

Past and future climate change, as well as interannual climate variability, could play an important role in driving changes in fire activity, on both regional and global scales. Fires can, in turn, affect climate via a variety of feedbacks, such as emissions of long-lived gases, short-lived gases, aerosols, and impacts on the land-surface. The need for integrated Earth system modelling in order to understand the role of fire in the Earth system has been stressed in the past [1]. This need still remains to be fulfilled. We know of no work to date that assesses

such feedbacks in a fully coupled modelling system that simulates fire, atmospheric composition, climate, and the land-surface simultaneously.

However, there has been substantial progress in developing models that are suitable for implementation in global climate modelling. The fire module of the Canadian Terrestrial Ecosystem Model [102] estimates the probability of fire occurrence depending on fuel availability and fuel moisture, and presence of an ignition source (anthropogenic or natural). Pechony and Shindell [3] developed a fire model that relies on a simple parameterisation involving temperature, humidity, precipitation, and the underlying vegetation density, with an option to take into account natural (lightning) and human ignitions, as well as human suppression. The option to use sophisticated but more computationally expensive global fire models has also become available in recent years, with one such example being LPFIRE, a new process-based fire model combining features from the LPJ family of fire models (primarily SPITFIRE [103]), in which fire is simulated as a function of ignitions and fire susceptibility, calculated from fuel amount, physical properties and moisture content.

Since the climate variables can be predicted online by an atmospheric model, and the vegetation density can be predicted by a land-surface model, which are both components that typically exist in current Earth system models (ESMs), fire parameterisations such as the above can be coupled with ESMs relatively easily. Simultaneously, such models can be developed further to calculate fire emissions in addition to fire occurrence and burned area, such as in studies [6,84] that used a modified version of the Community Land Model version 3.5 with a carbon-

nitrogen biogeochemical model and estimated fire emission changes between the past, present and future.

Currently, the above mechanistic fire occurrence/emission models are being implemented in some key global ESMs. This development will allow for including fire as a component in global climate simulations, and the potential to improve climate predictions, and will, at the same time, allow for studying global and regional changes in atmospheric composition and fire-generated pollution.

Major advances in fire modelling at a global scale will also depend on advances in the 'core' atmospheric components, such as improvements to subgrid parameterizations of convection and turbulence. Fire size and fuel consumption will be estimated less from empirical relationships and more from dynamical fire spread models, which currently exist only for high-resolution limited-domain models [104]. The simulated meteorology, in turn, will respond to fluxes of momentum, heat, and emissions from the fire. Lightning activity and plume heights will be estimated accordingly. This will make more sense as convective super-parameterizations [105] become more commonplace, but this is likely to be a decade away for CMIP-grade production GCMs, and will require commensurate improvements in fuel characterizations.

Assessing health and other impacts

Fires can have wide-ranging effects on surface air quality, both in the tropics and extra-tropics (see earlier section). Health effects of key anthropogenic pollutants such as particulate matter (i.e. aerosols) and ozone have been investigated

extensively, with some studies even documenting global effects [e.g. 106]. A few studies have specifically focused on the effects of fire emissions on health, such as the work by Marlier et al. [107], which examined climate variability (specifically, El Niño) as a potential driver of such effects in Southeast Asia. A key study [108] provided estimates of global mortality due to fire emissions, using an atmospheric model in conjunction with satellite observations to estimate pollutant levels, and suggested that landscape fires lead to 339,000 deaths annually, with the most vulnerable regions being sub-Saharan Africa and Southeast Asia, and the situation being worse during El Niño years. These studies have mostly focused on particulate matter (PM) and ozone effects, but as we have noted earlier, health effects from fires could also result from emissions of toxic NMVOCs, such as benzene [22].

The link between climate variations and health impacts from fires has implications for future population health [109]. Emerging integrated modelling capabilities, where future fire activity is simulated simultaneously with climate, and where atmospheric composition effects of such fire changes are also calculated, will facilitate studying the influences of climate change on health. Furthermore, such advances are expected to trigger a closer dialogue between scientists working on the physical aspects of climate change and fire, and public health scientists. On a broader perspective, cross-fertilisation and dialogue between different communities can facilitate the assessment and understanding of other impacts of fires not immediately linked to air pollution, such as those on ecosystems, agriculture, infrastructure, and the economy.

Conclusions

The effects of fire on atmospheric composition depend on the region of emission and constituent of interest. North America and Europe have been investigated more thoroughly, while Southeast Asia, South America, and Siberia have received specific scientific attention more recently. Africa, remote oceanic areas and polar regions have been far less studied, and the understanding of such effects there relies heavily on satellite information and modelling. The species that have been more extensively investigated are ozone and aerosols (especially BC), with fewer studies focusing on other constituents, such as NMVOCs and NO_x . Fires can lead to substantial radiative forcing due to their emissions, but the magnitude of those effects remains uncertain. Even more uncertain and unexplored are the climate responses caused by fire emissions. It is therefore important to conduct further modelling for understanding such effects better, and to aim for integrated systems that include fire as a component interacting with climate, atmospheric chemistry, and the biosphere. For this modelling to be accurate, however, we need sustained observations that will lead to a better characterisation of the emissions from fires. Currently, and due to substantial disagreements between emissions datasets provided by different groups, we recommend that modelling studies based on single emissions estimates should be interpreted cautiously. Nevertheless, the advances that have been made over the past decade on both the observational and the modelling front are remarkable, and over the next decades the community is expected to be gaining progressively more insight into the role of fire in the Earth system, and how it affects human society and ecosystems.

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Table 1: Global mean annual emissions estimates (in Tg) for key species from GFEDv3 ([12]; from <http://www.falw.vu/~gwerf/GFED/GFED3/tables/>), FINNv1 [13], GFAS [15] and FLAMBE [14]. GFED and GFAS emissions factors are based on those of [11], FINN emissions factors are based primarily on those from [17]. TPM stands for “total particulate matter”.

	CO ₂	CO	CH ₄	NO _x	OC	BC	TPM
GFEDv3 (2003-2011)	6508	329	17	9	18	2.0	44
FINNv1 (2005-2010)	7323	373	18	13	23	2.2	59
GFAS (2003-2008)	6907	352	19	10	18	2.0	45
FLAMBE (2006-2008)	-	-	-	-	-	-	110



Figure 1: Remote-controlled drone over South Sumatra during the brief haze event of September-October 2014. Trace gas measurements from the drone are being used to better constrain emissions factors from tropical peat burning. (Courtesy Guido van der Werf, VU Amsterdam)