



Wildfire air pollution hazard during the 21st century

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Abstract. Wildfires pose a significant risk to human livelihoods and are a substantial health hazard due to emissions of toxic smoke. Previous studies have shown that climate change, increasing atmospheric CO₂, and human demographic dynamics can lead to substantially altered wildfire risk in the future, with fire activity increasing in some regions and decreasing in others. The present study re-examines these results from the perspective of air pollution risk, focussing on emissions of airborne particulate matter (PM_{2.5}), combining an existing ensemble of simulations using a coupled fire–dynamic vegetation model with current observation-based estimates of wildfire emissions and simulations with a chemical transport model. Currently, wildfire PM_{2.5} emissions exceed those from anthropogenic sources in large parts of the world. We further analyse two extreme sets of future wildfire emissions in a socio-economic, demographic climate change context and compare them to anthropogenic emission scenarios reflecting current and ambitious air pollution legislation. In most regions of the world, ambitious reductions of anthropogenic air pollutant emissions have the potential to limit mean annual pollutant PM_{2.5} levels to comply with World Health Organization (WHO) air quality guidelines for PM_{2.5}. Worst-case future wildfire emissions are not likely to interfere with these annual goals, largely due to fire seasonality, as well as a tendency of wildfire sources to be situated in areas of intermediate population density, as opposed to anthropogenic sources that tend to be highest at the highest population densities. However, during the high-fire season, we find many regions where future PM_{2.5} pollution levels can reach dangerous levels even for a scenario of aggressive reduction of anthropogenic emissions.

1 Introduction

Wildland fires – or in short wildfires – are burning events that occur in natural or semi-natural landscapes such as (managed or unmanaged) forests, shrublands, or grazing lands including savannahs. They are a major natural hazard (Bowman et al., 2009) and an important source of air pollutants (Langmann, 2009), which can impact air pollution thousands of kilometres downwind (Lee et al., 2005). Wildfires also play an important role in several atmospheric chemistry–climate feedback mechanisms (Fiore et al., 2012). Emissions of fine aerosol particles, i.e. particulate matter up to an aerodynamic diameter of 2.5 µm (PM_{2.5}), are of particular health concern, with no known safe concentration in air, as noted by the World Health Organization (WHO 2006). Wildfires can be an important source in large, more remote areas (Granier et al., 2011, van der Werf et al., 2010), even though anthropogenic emissions are higher globally. There is a widely held view among both the general public and members of the research community that wildfire occurrence and severity have been increasing in recent decades and will continue to increase due to climate change (Doerr and Santin, 2016). Moreover, efforts to reduce anthropogenic emissions (e.g. EEA, 2014) will increase the relative importance of other emission sources.

Climate warming has already led to more frequent hot and dry weather in many parts of the globe, increasing the probability of wildfires (Flannigan et al., 2009), and this is expected to continue into the future. Studies based on calculated fire severity indices under climate change argue for large increases in burned area (Flannigan et al., 2005 for Canada; Amatulli et al., 2013, for southern Europe) and

resultant pollutant emissions (Spracklen et al., 2009; Yue et al., 2013, for the western US), with some regional exceptions of declining emissions due to increased precipitation (Yue et al., 2015, for a few subregions in northern Canada). However, a long-term increase in the length of the fire season or in weather conditions conducive to wildfires does not necessarily lead to increases in burned area (Doerr and Santin, 2016). This is because on longer timescales vegetation responds not only to climate change but also directly to rising atmospheric CO₂ levels (Buitenwerf et al., 2012; Donohue et al., 2013). While CO₂ fertilization will lead to increased fuel load, enhancing emissions also leads to an increase in woody as opposed to herbaceous vegetation, with on average lower emissions due to decreased fire spread in less flammable shrublands (Kelley and Harrison, 2014; Knorr et al., 2016a). Indeed, simulations with coupled fire–vegetation or statistical models generally show less increase in burned area (Kloster et al., 2010; Knorr et al., 2016b) or number of fires (Krwachuk et al., 2009) when accounting not only for climate but also for these vegetation effects.

Further factors that have so far received less attention are growth and changes in human population size and distribution. Contrary to common perception, higher population density tends to be associated with lower wildfire risks when measured by burned area (Archibald et al., 2009, 2010; Lehsten et al., 2010; Knorr et al., 2014; Bistinas et al., 2014), even though higher population density in rural and remote regions tends to lead to more but on average smaller fires (Archibald et al., 2009, 2010). This can be explained by the concept of the ignition-saturated fire regime, which is reached at very low levels of population density. Above this level, human impact manifests itself less in enhancing burned area (by igniting fires), but more by creating barriers to and suppressing fire spread, thus reducing area burned (Guyette et al., 2002). Indeed, coupled vegetation–fire models that include the effects of changing human population size and spatial distribution suggest a reduced rate of increase of fire activity during the 21st century compared to simulations that do not account for demographic changes (Kloster et al., 2010). Some studies even showed a decline in burned area (Knorr et al., 2016b) or emissions (Knorr et al., 2016a) for moderate levels of climate change, when combined with slow urbanization and high population growth. These results are backed by observational evidence of a long-term declining trend in past fire activity or emissions from wildfires (Marlon et al., 2008; Wang et al., 2010; van der Werf et al., 2013), and more recent negative trends in northern Africa that have been related to the expansion of cropland (also resulting from increasing population density; Andela and van der Werf, 2014). Furthermore, the impacts of wildfires on human society are also largely determined by population growth and spatial distribution (Knorr et al., 2016b). It is therefore important to consider not only climate and CO₂ scenarios, but also scenarios of demographic changes.

The overarching research question addressed in this paper is whether socio-economic developments influencing both greenhouse gas emissions as well as human population size and spatial distribution might impact wildfire emissions enough to make a difference for meeting the WHO air quality target, provided anthropogenic PM_{2.5} emissions are reduced aggressively. The work in this study takes the following steps towards this end: building on a similar study for Europe (Knorr et al., 2016c) for computing emissions, we use a state-of-the-art chemical transport model to compute future levels of human exposure to PM_{2.5} using observation-based wildfire emissions, combined with relative changes in emissions from vegetation–fire model simulations. Our analysis focuses on the relative importance of changes in global wildfire emissions for air quality and atmospheric pollutant load, as compared to anthropogenic sources.

2 Methods

2.1 Vegetation–fire model and driving data

We use the LPJ-GUESS global dynamic vegetation model (Smith et al., 2001; Ahlström et al., 2012) coupled to the global semi-empirical fire model SIMFIRE (Knorr et al., 2014), with details given by Knorr et al. (2016a). In short, LPJ-GUESS is a patch-scale dynamic vegetation model that represents age cohorts of perennial vegetation and computes vegetation establishment and growth, allocation of carbon pools in living plants, and turnover of carbon in plant litter and soils. SIMFIRE provides burned area to LPJ-GUESS on an annual basis, which then evokes plant mortality according to a probability dependent on plant functional type (PFT). Specified fractions of plant litter and live leaf biomass are burnt and emitted into the air in a fire, while the remaining biomass of the killed vegetation is transferred to the litter pool of LPJ-GUESS (see Knorr et al., 2012). Population data needed to drive SIMFIRE are based on gridded data from HYDE 3.1 (Klein-Goldewijk et al., 2010) up to 2005 and are then rescaled using per-country relative growth in rural and urban population, retaining the urban masks of the HYDE data. Grid cells with more than 50 % past or future cropland area in either the RCP6.0 or 4.5 land use scenarios (Hurtt et al., 2011; see Sect. 2.2) were excluded from the calculations (see Knorr et al., 2016a, b, for details).

In order to compute emissions of chemical species, we use the emission factors of the Global Fire Emissions Database version 4 (GFED4; van der Werf et al., 2010, based mainly on Akagi et al., 2011; see <http://www.globalfiredata.org>), which are fixed ratios between emission rates of various pollutant species and rates of combustion of dry biomass differentiated by where the fire occurs: (1) savannahs and grasslands, (2) tropical, (3) boreal, and (4) temperate forests. In order to select the appropriate emission factor, we assign a grid cell to (1) if the PFT with the largest leaf area index at full leaf

development is a grass, to (2) if it is a tropical tree, and to (3) or (4) if it is a boreal or temperate tree (see Knorr et al., 2012, for a list of PFTs used).

2.2 Simulations and scenarios

Climate simulations were driven by output from an ensemble of eight global climate models from the Climate Model Intercomparison Project 5 (CMIP5; Taylor et al., 2012) for two climate scenarios based on the Representative Concentration Pathways (van Vuuren et al., 2011) RCP4.5 with a moderate and RCP8.5 with a high degree of climate change. Simulations for 1901 to 2100 are carried out on a global equal-area grid with $1^\circ \times 1^\circ$ spatial resolution at the Equator, but constant east–west spacing of the grid cells when moving towards the poles in order to keep the grid cell area constant (Knorr et al., 2016a). These climate scenarios were combined with population and urbanization projections following the shared socio-economic pathways (SSPs; Jiang, 2014). The SSPs are based on qualitative narratives of five different development pathways, which have been translated into quantitative projections of a range of socio-economic, demographic, and biophysical factors. Here, we focus on two combinations that represent the highest and lowest wildfire combusted carbon emissions globally (Knorr et al., 2016a). These are RCP8.5 (high greenhouse gas emissions, strong warming) combined with SSP5 (rapid fossil-fuel-driven economic growth with globally low population growth and fast urbanization leading to land abandonment and increased wildfire activity), and RCP4.5 (moderate greenhouse gas emissions and climate warming) combined with SSP3 (globally high population growth and slow urbanization leading to increased fire suppression). Note, however, that in contrast to developing countries and the world as a whole, high-income countries have high population growth for SSP5, but low population growth for SSP3.

In addition to the emissions simulated by LPJ-GUESS–SIMFIRE, we also use the GFED4.1s observation-based emission fields for wildfires (van der Werf et al., 2010, updated using Randerson et al., 2012, and Giglio et al., 2013) aggregated to $0.5^\circ \times 0.5^\circ$ resolution and then rescaled in time by country or region (following the methodology of Knorr et al., 2016c). For larger countries, scaling is done by subnational regions, which were chosen in such a way as to isolate major fire areas found in GFED4.1s (for a list of regions and/or countries, see Table S1 in the Supplement). The use of country boundaries and performing the analysis at $0.5^\circ \times 0.5^\circ$ instead of the 1° resolution used by LPJ-GUESS–SIMFIRE better accounts for the high degree of fire policy or cultural impact on fire regimes (Bowman et al., 2009).

For wildfires, we use the sum of boreal forest fires, temperate forest fires, and savannah fires from GFED4.1s. Agricultural waste burning from GFED4.1s has been excluded from the calculations. Instead, we use anthropogenic emissions that include agricultural burning from the ECLIPSE data set

(Granier et al., 2011). Deforestation fires (caused by deforestation activities) and peat fires (fires occurring in forested or non-forested peatlands; see van der Werf et al., 2010) were found to be minor sources globally despite their regional importance mainly in South East Asia (Fig. S1 and Table S2 in the Supplement).

In contrast to Knorr et al. (2016c), in which changes in the spatial distribution of population within a country did not affect predicted wildfire emissions, here we also account for demographic effects on the grid-cell scale. To do so, we combine a scalar accounting for climate and vegetation effects, f_{cv} , which is uniform in space across each region and/or country, with a scalar accounting for population effects, f_p , which is applied at each grid cell separately:

$$E^S(x, y, m) = f_{cv}^S(R(x), y) \times f_p(\Delta p'(x, y)) \times E_{GFED}^S(x, m), \quad (1)$$

with E^S the rescaled per-grid-cell emissions of chemical species S , x the geographic location on the $0.5^\circ \times 0.5^\circ$ grid used for the analysis, y year, m month of the year, $R(x)$ the country or region found at location x , and E_{GFED}^S the (per-grid-cell) emission climatology of species S from GFED 4.1s averaged from 1997 to 2014. The population effect, f_p , is equal to the population multiplier of SIMFIRE (Knorr et al., 2016a):

$$f_p(\Delta p') = \exp(-0.0168 \times \Delta p'), \quad (2)$$

with $\Delta p'(x, y) = p'(p(x, y)) - p'(p(x, y_0))$, in which $p'(p)$ is the minimum of population density p and 100 inhabitants per km^2 . Future emission levels are computed relative to emissions during the reference year $y_0 = 2010$. The cap at 100 km^{-2} , which is only used for scaling observation-based inventories by LPJ-GUESS–SIMFIRE output (not by SIMFIRE itself), is used to prevent unrealistically large relative increases in emissions resulting from the scaling procedure when population density decreases from present values that are far above 100 km^{-2} . In other words, we consider areas with a population density above 100 km^{-2} to be essentially wildfire free. The combined effect of climate and vegetation on emissions is defined as

$$f_{cv}^S(R, y) = \left\{ \frac{\sum_{x' \in R} E_{SIM}^S(x', y)}{\sum_{x' \in R} E_{SIM}^S(x', y_0)} \right\} / \dots \left\{ \frac{\sum_{x' \in R} f_p(p(x', y) - p(x', y_0)) E_{GFED}^S(x', m)}{\sum_{x' \in R} E_{GFED}^S(x', m)} \right\}. \quad (3)$$

Here, E_{SIM}^S values are LPJ-GUESS–SIMFIRE emissions of species S computed on the 1° equal-area grid. The sums are carried out over all grid cells x' of the 1° equal-area grid over all grid cells that belong to region and/or country R . The first term in curly brackets is the SIMFIRE-simulated relative

change in emissions or region R by year y (shown in Fig. S2 in the Supplement), which is divided by the projected change in emissions only due to changes in population density (second term in curly brackets; see Fig. S3 in the Supplement for a map of projected changes only due to population density, i.e. $f_p(p'(x, y) - p'(x, y_0))$ for $y = 2090$). Finally, we compute future projected emissions of species S as the 21-year climatological mean around 2090:

$$E_{2090}^S(x, m) = \sum_{y \in [2080, 2100]} E^S(x, y, m). \quad (4)$$

Countries for which 90 % or more of the grid cells of the LPJ-GUESS grid have either a current or future cropland fraction of ≥ 50 % (highly agricultural regions: Moldavia and Bangladesh), or for which LPJ-GUESS simulates zero current emissions in at least one simulation (Greenland) were excluded from this scaling procedure by setting $f_{cv}^S(R, y) = f_p(p) = 1$. Note that the procedure retains the seasonal cycle of the GFED4.1 emissions, $E_{GFED}(m)$, by scaling each month by the same factor.

The computed seasonal cycle of anthropogenic emissions of CO, NH₃, SO₂, NO_x, black carbon, and organic carbon (at monthly resolution) for current conditions and 2090 were provided as input to the Community Atmosphere Model including interactive chemistry (CAM-Chem; Lamarque et al., 2012). In the present configuration, CAM-Chem simulates the aerosol distributions for all types (i.e. sulfate, nitrate, black carbon, organic carbon, sea salt, and mineral dust). From those, the PM_{2.5} distribution is calculated using all components except dust or sea salt since those are not affected by biomass burning, and assuming all component mass to be present below 2.5 μm . For current emissions we take $E_{GFED}^S(x, m)$, and for 2090 emissions $E_{2090}^S(x, m)$ (Eq. 4). Anthropogenic emissions are constant over the year.

The configuration of CAM-Chem is identical to the one used in the recent Chemistry-Climate Model Initiative simulations discussed in Tilmes et al. (2016) under REF-C1 (specified sea-surface temperatures and sea-ice distribution), except for using a higher horizontal resolution of 0.9° latitude $\times 1.25^\circ$ longitude. The model has 26 vertical layers from the surface to approximately 40 km. CAM-Chem is used here as a chemical transport model, with the meteorology being the same between simulations with different emission fields, thus excluding the effect of changing atmospheric composition on meteorology. This is done so that short simulations are sufficient to identify the chemical impacts of different emission scenarios. Emissions of sea salt, dust, and biogenic volatile organic compounds (VOCs, i.e. isoprene and monoterpenes, which are precursors to secondary organic aerosols) are also identical between the different simulations, and are computed as in Tilmes et al. (2016). For all species, emissions (including biomass burning) are included as flux boundary conditions to the vertical diffusion module and are therefore quickly (within hours) redistributed within the boundary layer.

The current representation of aerosols in CAM-Chem has been extensively tested and compared with observations. In particular, Lamarque et al. (2012) provide a comparison of present-day observations of the IMPROVE network over the conterminous US, indicating an overall good representation of the probability density function for all species considered in the present study. In addition, Shindell et al. (2013) have shown that CAM-Chem indicated the lowest bias of the models when compared to observed aerosol optical depth. Finally, CAM-Chem results have been used in several health impact studies (West et al., 2013; Silva et al., 2013, 2016) and is usually very consistent with other chemistry–climate models used for those analyses. Four simulations are carried out for a period of 25 months each, and a mean annual cycle is computed from months 2 to 25. While there is some residual inter-annual variability in the 2 meteorological years simulated by the model, this signal is small compared to the impact associated with the changes in emissions (not shown).

2.3 Analytical framework

Our analysis focuses on two time windows, current conditions and 2090. To assess the relevance of wildfire PM_{2.5} emission rates, we compare them to those from anthropogenic sources and also judge simulated surface concentrations by their proximity to the WHO air quality guidelines of $10 \mu\text{g m}^{-3}$ on an annual average, keeping in mind that there is no established safe upper limit and that the target was set considering background concentrations of $3\text{--}5 \mu\text{g m}^{-3}$ in North America and western Europe.

For anthropogenic emissions, we use the ECLIPSE-GAINS-v4a data (Amann et al., 2011) developed as part of the ECLIPSE project (Granier et al., 2011; Klimont et al., 2013; Stohl et al., 2015). This data set provides two scenarios: current legislation (CLE) and maximum feasible reductions (MFRs) on top of business-as-usual projections until 2050 from the Energy Technology Projections study, which is considered roughly equivalent to RCP6.0, from the International Energy Agency (IEA, 2012). MFR corresponds to a policy- and technology-driven abatement scenario, implementing all currently known technologies at a reasonable cost, with the aim, among others, to lower PM_{2.5} emissions to levels with limited health impacts (Amann et al., 2011). For the present, we use emissions for 2010 under the CLE scenario. Following Knorr et al. (2016c), we estimate 2090 CLE emissions assuming constant per capita emissions after 2050, but changing population densities according to the SSP3 scenario, which directly affects magnitude and spatial patterns of emissions. For MFR, 2090 emissions are assumed to be half of the corresponding 2050 levels (i.e. somewhat optimistic compared with Braspenning-Radu et al., 2016, for example). In principle the emissions under CLE and MFR conditions may differ also for different SSP and climate mitigation assumptions (Rao et al., 2016; Braspenning-Radu et al., 2016). However, the assumptions above can be seen

Table 1. Scenarios and scenario differences considered in the analysis.

Case	CAM-Chem	Anthropogenic emissions	Wildfire scenario
0	x	Current	Current
1	x	MFR (lowest)	SSP3/RCP4.5 (lowest)
2	x	MFR (lowest)	SSP5/RCP8.5 (highest)
3	x	CLE (highest)	SSP5/RCP8.5 (highest)
4		CLE (highest)	SSP3/RCP4.5 (lowest)
Assessment of			
2–1		Impact of wildfire scenario on PM _{2.5} emissions	
3–2		Impact of air quality policy scenario on PM _{2.5} emissions	

as a schematic approximation of a wide range of possible air pollution emission futures that have become available in the recent literature.

To facilitate the regional aspects of our analysis, we use a global map of nine major world regions (see Fig. S4 in the Supplement). Of these, three belong to the high-income group of countries of the SSP scenarios (see Jiang and O’Neill, 2015): high-income Europe, Australia and New Zealand, and North America. Countries of Europe belonging to the middle-income group were assigned to the region eastern Europe and central Asia, which also includes Russia. High-income countries of the Middle East (Israel and oil-rich states of the Persian Gulf) or East Asia (Japan and South Korea), which only account for a very small fraction of wildfire emissions in their respective regions, have been excluded from the analysis.

In this study, we address the question of whether there is a risk that the combined direct (as estimated by changing population patterns) and indirect impacts (through climate change) of human activities on wildfire pollutant emissions will compromise meeting the WHO guideline value of $10 \mu\text{g m}^{-3}$, under a scenario in which anthropogenic PM_{2.5} emissions are reduced aggressively. The range of plausible future air quality policy scenarios is spanned by the difference between our projections using MFR and CLE assumptions. For a range of plausible wildfire emission scenarios, we consider the combinations SSP5/RCP8.5 (highest) and SSP3/RCP4.5 (lowest global wildfire emissions). Of the possible four emission combinations, we select three in order to assess the impact of either the plausible range of wildfire or of air quality policy scenarios (see Table 1). These three scenarios plus current emission fields are used for simulating present and future (2090) PM_{2.5} surface concentrations with CAM-Chem.

3 Results

3.1 Comparison of wildfire and anthropogenic pollutant emissions

In order for wildfire emissions to be relevant for atmospheric pollution levels, at least two conditions should be met: (1) they need to be of a similar or greater magnitude compared to anthropogenic sources and (2) they should be in or close to populated areas. Therefore, we first compare emission levels of both types of sources for the current and future time slices. Figure 1 shows areas where wildfire emissions currently exceed those from anthropogenic sources (in either red or light blue; shown in all panels). At first, these regions appear to lie in relatively remote areas of wildfire-prone regions (see Fig. S5 in the Supplement, e.g. the boreal forest zones of Canada and Alaska, eastern Siberia, the western US, the Brazilian interior, and in Africa away from the main population centres of Nigeria, Ethiopia, and Kenya). A breakdown of emissions by population density shown for the nine world regions (see Fig. S4 in the Supplement) shows that current (or future) anthropogenic emissions display a universal increase with increasing population density (solid blue lines in Fig. 2). Wildfire emissions also often increase with increasing population density and only for North America do per-area emissions decrease with increasing population density across the entire range of population densities (dashed blue lines in Fig. 2, i.e. current wildfire emissions). Most of the remaining regions have peaked distributions with the highest per-area emissions in some intermediate population density category, and it is not the most remote and sparsely inhabited areas that have the highest emissions. Therefore, despite a dominance of anthropogenic emissions in the more densely populated areas, wildfire emissions are often found to be an important pollution source in regions with intermediate population density, meaning that they approach or even exceed anthropogenic sources for population densities in the range from 10 to 100 km^2 (sub-Saharan Africa, Latin America and the Caribbean, South and South East Asia, and Australia and New Zealand). This 10 to 100 km^2 category is significant not only because of its relatively high popu-

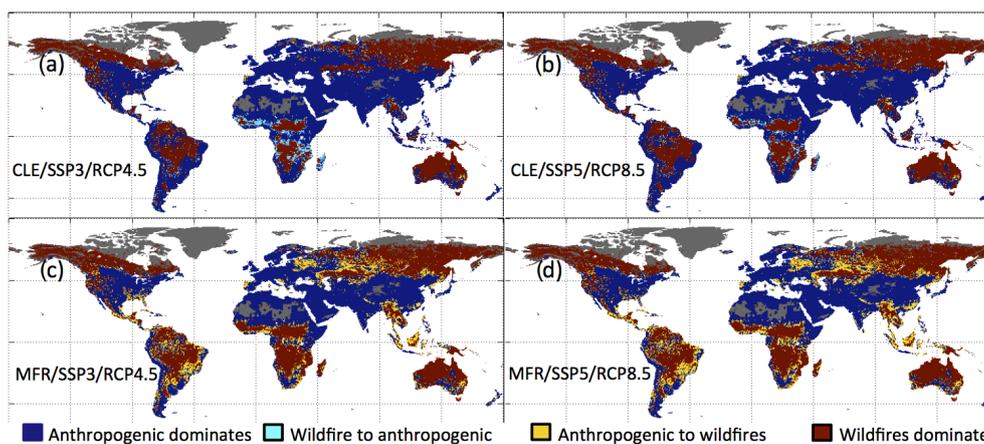


Figure 1. Dominant $\text{PM}_{2.5}$ source between anthropogenic and wildfire emissions at present and by 2090. Either source dominates if larger than the other. Cases are dominance for both periods, transition of dominance from the one to the other, or zero emissions in at least one period (grey areas). (a, b) CLE anthropogenic emission scenario (continuing high air pollutant emissions); (c, d) MFR anthropogenic scenario (maximum feasible reduction); (a, c) SSP3/RCP4.5 wildfire scenario (lowest future emissions); (b, d) SSP5/RCP8.5 wildfire scenario (highest future emissions).

lation density, but also because it represents the wildland–urban interface, which is often particularly prone to wildfires (Syphard et al., 2007).

For the simulated future, we either expect anthropogenic emissions to surpass those from wildfires in many regions (mainly in Africa, light blue areas in Fig. 1a and b) for the CLE scenario or the reverse for the MFR scenario, where wildfire emissions surpass anthropogenic sources in a wide range of regions (yellow areas in Fig. 1c, d: South America, Central America, Africa, eastern and southern Europe, central Asia, South East Asia, and southern China). This dominant role of the anthropogenic emission scenario is largely independent of the wildfire emission scenario (i.e. the difference between Fig. 1a and b or between Fig. 1b and d is much smaller than the difference between Fig. 1a and b on the one hand and Fig. 1c and d on the other hand). The strongest impact of the wildfire emission scenario is found for sub-Saharan Africa for the CLE scenario, in which SSP3/RCP4.5 shows many more regions newly dominated by anthropogenic emissions than SSP5/RCP8.5 (Fig. 1a vs. Fig. 1b). This is due to declining wildfire emissions in that scenario (see Fig. S2a in the Supplement). The scenario in which wildfire emissions are most likely to become a relevant source of $\text{PM}_{2.5}$ emissions is represented by the combination MFR/SSP5/RCP8.5 (Fig. 1d and Fig. 2, red lines; see also Fig. S2b in the Supplement).

The MFR scenario assumes a decline in anthropogenic emissions by approximately 1 order of magnitude in areas with at least 10 people km^{-2} , with somewhat less decrease for the more sparsely populated categories (Fig. 2). When compared to this magnitude of change, the simulated increase in wildfire emissions for SSP5/RCP8.5 is much smaller throughout. The highest absolute increase for wildfire emis-

sions is found for sub-Saharan Africa (in the 1 to 100 km^{-2} categories), Latin America (0.1 to 1 km^{-2}), South and South East Asia (below 10 km^{-2}), and developing East Asia (1 to 100 km^{-2}). As a consequence, mainly of the reduction implicit in the MFR scenario, wildfire emissions approach or exceed anthropogenic emissions even in the most densely populated category ($> 100 \text{ km}^{-2}$) for sub-Saharan Africa, Latin America and the Caribbean, eastern Europe–Russia–central Asia, South and South East Asia, and Australia and New Zealand. Note that the areas of the population density categories shift as well (see dotted lines in Fig. 2 and Fig. S5 in the Supplement) and that the underlying population patterns used to compute the MFR scenario do not necessarily match those from SSP5.

3.2 Changing patterns of $\text{PM}_{2.5}$ pollutant exposure

Simulated changes in $\text{PM}_{2.5}$ concentrations between current conditions and 2090 for the high-wildfire-emission scenario combined with MFR (Fig. 3 blue to red line, corresponding to emissions in Fig. 2, same colours) indicate a reduction in $\text{PM}_{2.5}$ pollutant concentration by between one-half and three-quarters in the most densely populated category ($> 100 \text{ km}^{-2}$) in each world region, resulting from the large reductions in anthropogenic emissions. Both the current and future pollution levels are substantially lower in the most sparsely populated categories. For current emissions, only two regions show average anthropogenic concentrations above the WHO air quality target of $10 \mu\text{g m}^{-3}$ (developing East Asia, South Asia, and South East Asia; note the different axis scales), and none do for 2090. We emphasize that the results presented here do not include sea-salt- and dust-derived particulate matter and are not downscaled using information on the emissions attributable to urban regions. In fact, in

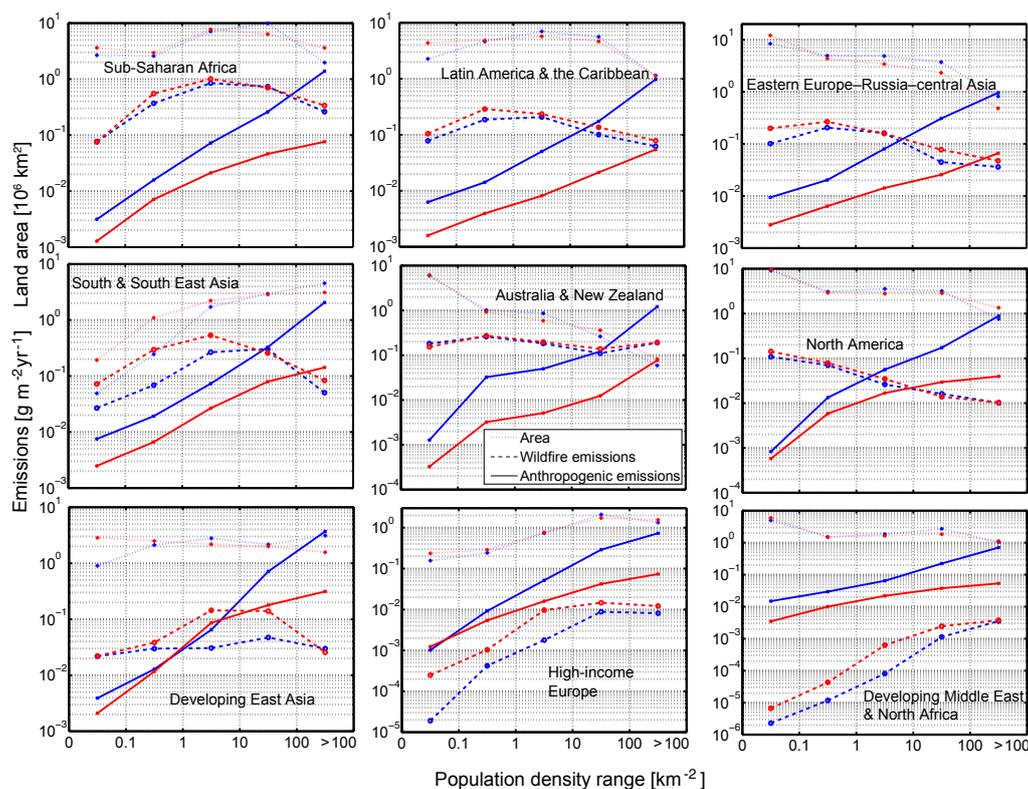


Figure 2. Predicted per-area annual $\text{PM}_{2.5}$ emissions against ranges of population density for wildfires and anthropogenic sources, at present (blue) and for 2090 (red) for the SSP5/RCP8.5 wildfire scenario (highest global emissions) and MFR anthropogenic emission scenario (maximum feasible reduction) for nine world regions. Also shown are changes in area extent of the population density categories.

Figs. 2 and 3 small areas with typical urban population densities above 1000 km^{-2} are included in the same category with the much larger areas in the 100 to 1000 km^{-2} range. Therefore, these results are likely to represent a lower limit of population-weighted $\text{PM}_{2.5}$ concentrations, which are consequently closer to the WHO guidelines. In general, relative changes in per-area emissions (Fig. 2) are much larger than relative changes in concentrations (Fig. 3), mainly due to the effect of long-range atmospheric transport of aerosols and precursor gases.

In contrast to the current situation with a steady increase in pollutant concentrations with population density (dark blue lines in Fig. 3), concentrations for 2090 peak at an intermediate level of population density in most regions (red lines: sub-Saharan Africa, Latin America and the Caribbean, eastern Europe–Russia–central Asia, Australia and New Zealand, and high-income Europe), reflecting the increased importance of wildfires for the spatial distribution of pollutant concentrations. This change over time is most pronounced for sub-Saharan Africa, where emissions from wildfires far outweigh anthropogenic $\text{PM}_{2.5}$ emissions by 2090 (Fig. 2).

The effect of the anthropogenic emission scenario can be seen by comparing the MFR and CLE scenarios for the case of the high-wildfire-emission scenario (red and green

lines in Fig. 3; see Table 1). CLE/SSP5/RCP8.5 compared to MFR/SSP5/RCP8.5 leads to large reductions in concentrations in pollutant concentrations in all regions by 2090, in particular for the most densely populated categories. Compared to this large effect of the anthropogenic emission scenario, the effect of the wildfire scenario (difference between high- and low-wildfire-emission scenarios, red and light blue lines in Fig. 3) is relatively small and only visible in sub-Saharan Africa, South and South East Asia, and developing East Asia.

Simulated spatial patterns of $\text{PM}_{2.5}$ concentrations for current conditions as well as for the CLE scenario (Fig. 4a and b) show large parts of central Africa as well as most of South, East, and South East Asia with concentrations above the WHO air quality guidance value. For MFR (Fig. 4c and d), however, only limited areas in central Africa show levels exceeding $10 \mu\text{g m}^{-3}$. For the high-wildfire scenario (SSP5/RCP8.5, Fig. 4d), concentrations are higher than for low wildfire emissions (SSP3/RCP4.5, Fig. 4c), but the corresponding areas are much more sparsely populated (see Fig. S4 in the Supplement). It appears therefore that under the MFR scenario, annual mean anthropogenic and wildfire-induced concentrations will remain below the WHO air quality guidance value for most areas of the globe. Even though

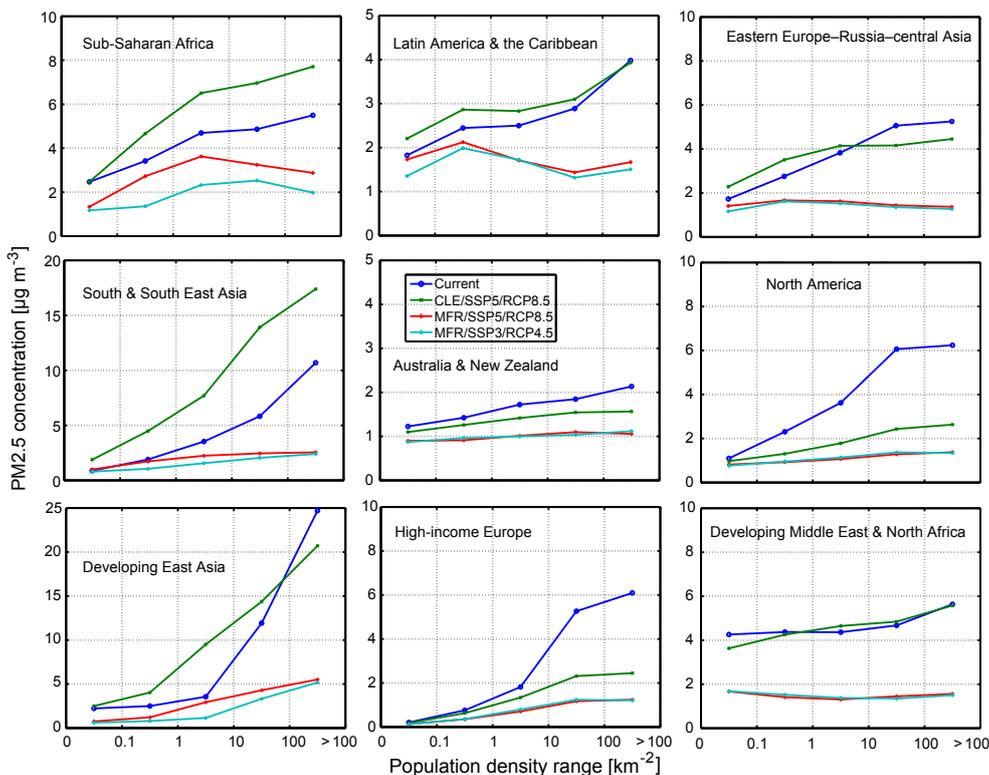


Figure 3. Predicted annual $\text{PM}_{2.5}$ concentrations against ranges of population density (excluding mineral dust and sea salt) for current conditions and three scenarios for 2090.

the previous analysis (Fig. 3) showed wildfire emissions becoming the dominant source for the high-wildfire scenario, it appears the levels of emissions are not high enough to bring concentrations above the annual WHO air quality value.

Further analysis hereafter focuses on monthly mean $\text{PM}_{2.5}$ concentrations, assuming this to be a health-related variable more appropriately reflecting the seasonality of fire emissions. We note that there is currently no guideline for monthly concentrations, but the WHO does provide guidelines for 24 h means that amount to $25 \mu\text{g m}^{-3}$. We here assume that formally declared safe monthly $\text{PM}_{2.5}$ concentrations would be somewhere between 10 and $25 \mu\text{g m}^{-3}$. When investigating monthly $\text{PM}_{2.5}$ concentrations, the picture changes considerably. For all scenarios, large but sparsely populated regions in central South America, northeastern Siberia, and northwestern Canada (see Fig. S4 in the Supplement) experience monthly pollution levels in excess of $10 \mu\text{g m}^{-3}$ (Fig. 5) and to a lesser extent $25 \mu\text{g m}^{-3}$. This result is largely independent of the anthropogenic emission scenario (comparing Fig. 5b with Fig. 5c and d). In regions that show large reductions of annual mean pollution levels for MFR, monthly maximum concentrations can still substantially surpass $10 \mu\text{g m}^{-3}$ (Africa, South East Asia, and, to some extent for SSP5/RCP8.5, southeastern China) or even $25 \mu\text{g m}^{-3}$ (Africa and South East Asia), even under an MFR scenario. The wildfire scenario is thus found to be of

globally limited but regionally important significance for air-pollution-related health impacts.

4 Discussion

In most regions of the world, decisive and effective reductions of anthropogenic air pollutant emissions will likely be able to limit pollutant levels below the WHO threshold of $10 \mu\text{g m}^{-3}$ annual mean $\text{PM}_{2.5}$ concentrations irrespective of the evolution of future wildfire emissions. This is mainly the result of the highly seasonal character of wildfire emissions, as well as a tendency of wildfire sources to be situated in areas of intermediate population density, as opposed to anthropogenic sources that tend to be highest at the highest population densities. We therefore see a shift in the highest pollution levels away from the most densely populated areas, which reduces the impacts of future human exposure to $\text{PM}_{2.5}$. However, as the example of the Russian wildfires in 2010 shows (Kaiser et al., 2012), high pollution levels even from single wildfires can persist over many weeks and thus pose a significant health threat over extended lengths of time. On a seasonal basis, we therefore find many regions where pollution levels can reach dangerous levels even for a scenario of aggressive reduction of anthropogenic emissions.

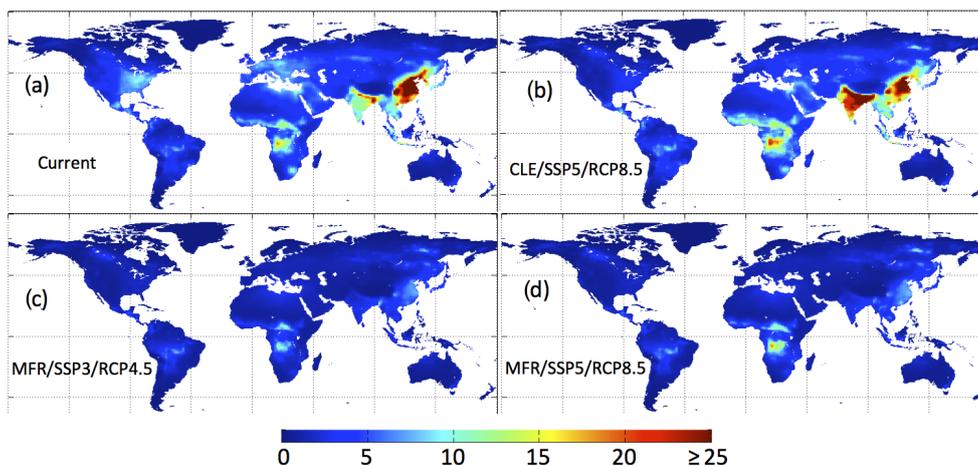


Figure 4. Simulated annual-mean anthropogenic and wildfire $\text{PM}_{2.5}$ concentration in microgrammes per cubic metre. (a) Current, (b) 2090 CLE/SSP5/RCP8.5, (c) 2090 MFR/SSP3/RCP4.5, and (d) 2090 MFR/SSP5/RCP8.5.

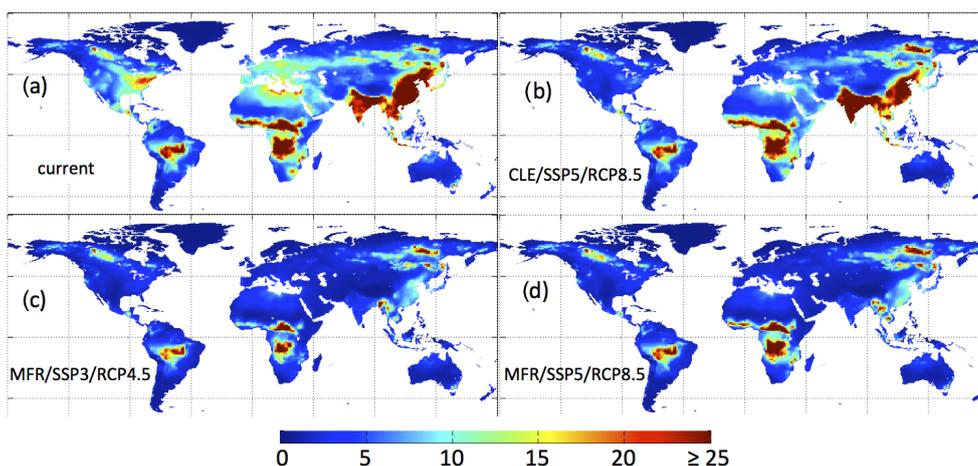


Figure 5. Simulated $\text{PM}_{2.5}$ concentration (excluding mineral dust or sea salt) in microgrammes per cubic metre for the month with highest concentration at each grid point. (a) Current, (b) 2090 CLE/SSP5/RCP8.5, (c) 2090 MFR/SSP3/RCP4.5, and (d) 2090 MFR/SSP5/RCP8.5.

Previous simulations with chemistry–climate models using RCP emission projections have already shown a strong future downward trend in East and South Asia, driven by reduced anthropogenic emissions, but no notable trend in Africa (Fiore et al., 2012). Knorr et al. (2016a) have shown a general picture of climate-driven fire emission increases, both for RCP4.5 and 8.5 scenarios, that may be overridden by demographic changes only in sub-Saharan Africa. This simulated future decline in Africa is in agreement with observations of currently already declining burned area that has been linked to demographic trends of increasing rural population for the northern part of sub-Saharan Africa (Andela and van der Werf, 2014). In the present study, southern China is identified as a new area of possible high human exposure to wildfire-generated air pollution under a scenario of rapid urbanization and population decline in rural areas. While forest fires in China may have received comparatively little at-

tention, they can still be substantial, with over 670 000 ha burnt annually between 1950 and 2010 (Shu et al., 2003; Su et al., 2015).

While any additional emission source of $\text{PM}_{2.5}$ poses a health risk (WHO 2006), wildfires are likely to be ignored by air quality policy if they emit considerably less than anthropogenic sources, in particular as their occurrence tends to be sporadic and of a short-term nature. One factor is that wildfire emissions are much more difficult to legislate given the difficulties of long-term fire suppression (Donovan and Brown, 2007). In this study, we find that in large parts of the world, wildfires are the main air pollutant source. While on an annual-mean basis they are unlikely to lift pollution levels above the WHO air quality guidance levels, they can become important sources on a seasonal basis.

In our simulations, air pollutant concentrations follow similar but more dispersed patterns compared to emissions, with

the highest levels in densely populated areas and the lowest levels in sparsely populated areas. In the future, in the case of strong reduction in anthropogenic sources, this pattern is predicted to shift to one in which the highest pollution levels are found in regions of intermediate population density for most regions (sub-Saharan Africa, Latin America and the Caribbean, and eastern Europe–Russia–central Asia), resembling more closely the pattern of wildfire emissions. This means that also due to their geographical distribution, wildfires pose a smaller risk to humans than anthropogenic emissions. Nevertheless, in our simulations under strong emission reduction from anthropogenic sources, the future trajectory of wildfire emissions has a discernible impact on air pollution in certain regions (sub-Saharan Africa, South and South East Asia, and developing East Asia) and is particularly relevant if we consider seasonal maxima in pollution levels. Even though the WHO recommendations are based on annual mean concentrations of $\text{PM}_{2.5}$, the WHO also states that health effects persist below these values. Fire emissions typically occur on the timescale of a week up to one or several months – the length of the fire season – and the WHO annual guidelines do not account for such monthly timescales. We hypothesize that, if a guidance level for monthly means were to be established, it would lie somewhere between 10 (annual) and $25 \mu\text{g m}^{-3}$ (daily WHO air quality guidance). These levels of $\text{PM}_{2.5}$ concentration are indeed frequently exceeded in our simulations even with the extremely low emission levels taken here for the MFR scenario.

It also needs to be taken into account that the $\text{PM}_{2.5}$ levels that are reported and compared to WHO or other air quality guidelines usually include some water content, as opposed to the simulated concentrations of dry aerosol mass, leading to a possible low bias of our simulations of the order of 30 to 50 % (Tsyro, 2005). Also, some emissions and components are not considered in our simulation (e.g. the ash component of fire emissions), or have a very high uncertainty (e.g. secondary aerosol formation associated with burning emissions, but also in general with vegetation emissions).

Significant health impacts are therefore very likely, even if this limit is exceeded only on a seasonal basis. For certain regions, it will be of critical importance whether future air quality policy objectives will converge to the current WHO guidelines, in which case fire management will become increasingly important. If anthropogenic emissions are aggressively curtailed (MFR scenario), wildfires in sub-Saharan Africa are predicted to decline less than anthropogenic sources, and in parts of South East Asia, southern China, and central South America climate change may even lead to new areas with wildfire emission levels relevant for air quality and the associated health impacts. In many boreal regions wildfires will also increase to levels at which they become pollution sources with relevant health impacts. Because past efforts aimed at a lasting reduction in wildfire activity have largely failed (Donovan et al., 2007; Doerr and Santin, 2016), it is questionable whether it is even possible

to devise policy measures aimed at bringing down wildfire emissions to avoid adverse health effects.

LPJ-GUESS–SIMFIRE only simulate wildfires. The predictions presented in this study therefore leave out the possibility of significant increases or decreases in deforestation or peat fire sources. Peat fires can be associated with considerable emissions (Page et al., 2002; Kajii et al., 2002), and forest conversion into cropland or pasture is often accompanied by burning (van der Werf et al., 2010). Both are of minor importance for air pollution except for South East Asia (see Fig. S1 and Table S2 in the Supplement), mainly in Indonesia (Field et al., 2009), where they are the dominant pollution source and occur even in more densely populated areas. In other regions, including Russia, peat fires are of minor importance. Whether or not future land-use change will lead to an increase or a decrease in deforestation is unknown. Based on integrated-assessment model realizations of the four RCPs, Hurtt et al. (2011) projected little increase or even a decline in future crop and pasture areas. However, in studies that assessed future land-use change from a broader perspective, a much larger range of crop and pasture changes emerged (Eitelberg et al., 2015; Prestele et al., 2016), which makes the relative change in deforestation vs. wildfires highly uncertain. In the present analysis, declining wildfire emissions are only predicted for sub-Saharan Africa, where it appears to be related to conversion of savannah to cropland (Andela and van der Werf, 2014).

Apart from the issue of dry vs. wet aerosols and the omission of some components that are difficult to model, there are additional limitations of this study. We expect that results will be affected by the presence of natural aerosols, such as mineral dust and sea salt, which – depending on location and time of year – could be significant fractions of the $\text{PM}_{2.5}$ concentrations (Monks et al., 2009). We do not evaluate changes in natural emissions of mineral dust, sea salt, or other naturally occurring emissions other than biomass burning. Also, the anthropogenic emission scenarios do not consider the benefits of climate mitigation scenarios and are based on rather crude assumptions regarding the development of emission controls beyond 2050, as the original scenarios do not consider developments beyond that year. The scenarios are thus only a subset of a large range identified in recent studies (Braspenning-Radu et al., 2016; Rao et al., 2016) and therefore call for a further evaluation of consistency in drivers across anthropogenic emissions, climate, and fire scenarios. The study furthermore only considers climatological monthly emissions during specified time windows, even though wildfire impacts on air quality can have large inter-annual (Jaffe et al., 2008) and intra-seasonal variations. We also did not account for relevant secondary emission products, such as ozone from wildfires, which can reach policy-relevant levels (Jaffe and Wigder, 2012). Other studies on the possible impact of climate change on wildfire-related air pollution hazards have concentrated on changes in meteorological conditions (Jacob and Winner, 2009; Tai

et al., 2010) instead of emissions. There has also been recent progress in the incorporation of injection height (Sofiev et al., 2012) into chemistry-enabled atmospheric general circulation models (Veira et al., 2015), which is not considered.

Nevertheless, to our knowledge, this is the first global-scale air quality study to consider changes in both climate and demographic drivers of air pollutant emissions from wildfires. Future work should aim at using general circulation models with realistic plume heights for a series of dedicated present and future time slices, combining observed plume height information, fire radiative energy data (for their finer temporal resolution), satellite-derived burned area (for better spatial coverage), projected emission changes from coupled dynamic vegetation–fire models (as the present study), and improved demographic scenarios accounting for changes in urban population density. Such studies would then also simulate the temporal statistics of pollution events on a daily timescale. Wildfire episodes can elevate $\text{PM}_{2.5}$ pollution levels to dangerous levels with serious health impacts (Haikerwal et al., 2015). Such results could then be used, for example, to assess for how many days the WHO 24 h $\text{PM}_{2.5}$ limit of $25 \mu\text{g m}^{-3}$ from the WHO air quality guidelines (WHO 2006) is exceeded as a result of wildfire emissions.

5 Summary and conclusions

- Globally, wildfire emissions are unlikely to thwart aggressive measures to reduce anthropogenic pollutant emissions enough to stay under the ambitious $10 \mu\text{g m}^{-3}$ annual-mean limit of the WHO.
- In a number of regions, wildfire emissions will remain or could rise above critical thresholds relevant for health policy, in particular when pollution levels during the fire season are considered. So far, there is no generally accepted method for wildfire management that has been shown to lead to lasting reductions in fire activity or emissions.
- Demographic changes appear to be the main drivers of the expected changes in wildfire emissions in sub-Saharan Africa. For a scenario of high population growth and slow urbanization, anthropogenic sources could surpass air pollutant emissions from wildfires in most populated areas. Exposure of humans to $\text{PM}_{2.5}$ in sub-Saharan Africa is expected to drop if measures are put in place to reduce anthropogenic emissions, but wildfires may remain as a health-relevant pollution source in a scenario of fast urbanization and low population growth.

Data availability. RCP historical and scenario CO_2 concentrations from the International Institute for Applied Systems Anal-

ysis (IIASA) are available at <http://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=download>, population density data according to HYDE 3.1 from PBL at <http://themasites.pbl.nl/tridion/en/themasites/hyde/download/index-2.html>, SSP population and urbanization scenarios by country from IIASA at <https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=countries>, GFED 4.1s fire emissions from the Free University of Amsterdam available from <http://www.globalfiredata.org>, and ECLIPSE GAINS 4a emissions from the ECCAD web portal at http://eccad.sedoo.fr/eccad_extract_interface/JSF/page_login.jsf.

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Author contributions. W. Knorr conceptualized the study, carried out the analysis, and wrote the first draft of the paper. J. F. Lamarque performed the CAM-Chem simulations. All authors contributed to discussions and writing.

Competing interests. The authors declare that they have no conflict of interest.

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References

- Ahlström, A., Schurgers, G., Arneth, A., and Smith, B.: Robustness and uncertainty in terrestrial ecosystem carbon response to CMIP5 climate change projections, *Environ. Res. Lett.*, 7, 044008, <https://doi.org/10.1088/1748-9326/7/4/044008>, 2012.
- Akagi, S. K., Yokelson, R. J., Wiedinmyer, C., Alvarado, M. J., Reid, J. S., Karl, T., Crounse, J. D., and Wennberg, P. O.: Emission factors for open and domestic biomass burning for use in atmospheric models, *Atmos. Chem. Phys.*, 11, 4039–4072, <https://doi.org/10.5194/acp-11-4039-2011>, 2011.
- Amann, M., Bertok, I., Borcken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., and

- Rafaj, P.: Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications, *Environ. Modell. Softw.*, 26, 1489–1501, 2011.
- Amatulli, G., Camia, A., and San-Miguel-Ayanz, J.: Estimating future burned areas under changing climate in the EU-Mediterranean countries, *Sci. Total Environ.*, 450, 209–222, 2013.
- Andela, N. and van der Werf, G. R.: Recent trends in African fires driven by cropland expansion and El Nino to La Nina transition, *Nat. Clim. Change*, 4, 791–795, 2014.
- Archibald, S., Roy, D. P., van Wilgen, B. W., and Scholes, R. J.: What limits fire? An examination of drivers of burnt area in Southern Africa, *Global Change Biol.*, 15, 613–630, 2009.
- Archibald, S., Scholes, R. J., Roy, D. P., Roberts, G., and Boschetti, L.: Southern African fire regimes as revealed by remote sensing, *Int. J. Wildland Fire*, 19, 861–878, 2010.
- Bistinas, I., Harrison, S. P., Prentice, I. C., and Pereira, J. M. C.: Causal relationships versus emergent patterns in the global controls of fire frequency, *Biogeosciences*, 11, 5087–5101, <https://doi.org/10.5194/bg-11-5087-2014>, 2014.
- Bowman, D. M. J. S., Balch, J. K., Artaxo, P., Bond, W. J., Carlson, J. M., Cochrane, M. A., D'Antonio, C. M., DeFries, R. S., Doyle, J. C., Harrison, S. P., Johnston, F. H., Keeley, J. E., Krawchuk, M. A., Kull, C. A., Marston, J. B., Moritz, M. A., Prentice, I. C., Roos, C. I., Scott, A. C., Swetnam, T. W., van der Werf, G. R., and Pyne, S. J.: Fire in the earth system, *Science*, 324, 481–484, 2009.
- Braspenning-Radu, O., van der Berg, M., Deetman, S., Klimont, Z., Janssens-Maenhout, G., Muntean, M., Dentener, F. J., and van Vuuren, D. P.: Exploring synergies between climate and air quality policies using long-term global and regional emission scenarios, *Atmos. Environ.*, 140, 577–591, 2016.
- Buitenwerf, R., Bond, W. J., Stevens, N., and Trollope, W. S. W.: Increased tree densities in South African savannas: >50 years of data suggests CO₂ as a driver, *Global Change Biol.*, 18, 675–684, 2012.
- Doerr, S. H. and Santín, C.: Global trends in wildfire and its impacts: perceptions vs. realities in a changing world, *Philos. T. R. Soc. B*, 371, 20150345, <https://doi.org/10.1098/rstb.2015.0345>, 2016.
- Donohue, R. J., Roderick, M. L., McVicar, T. R., and Farquhar, G. D.: Impact of CO₂ fertilization on maximum foliage cover across the globe's warm, arid environments, *Geophys. Res. Lett.*, 40, 3031–3035, 2013.
- Donovan, G. H. and Brown, T. C.: Be careful what you wish for: the legacy of Smokey Bear, *Front. Ecol. Environ.*, 5, 73–79, 2007.
- Eitelberg, D. A., Vliet, J., and Verburg, P. H.: A review of global potentially available cropland estimates and their consequences for model-based assessments, *Global Change Biol.*, 21, 1236–1248, 2015.
- EEA: Air quality in Europe – 2014 report, European Environmental Agency, Luxembourg, Report No. 5/2014, 80 pp., <https://doi.org/10.2800/22775>, 2014.
- Field, D. F., van der Werf, G. R., and Shen, S. S. P.: Human amplification of drought-induced biomass burning in Indonesia since 1960, *Nat. Geosci.*, 2, 185–188, 2009.
- Fiore, A. M., Naik, V., Spracklen, D. V., Steiner, A., Unger, N., Prather, M., Bergmann, D., Cameron-Smith, P. J., Cionni, I., and Collins, W. J.: Global air quality and climate, *Chem. Soc. Rev.*, 41, 6663–6683, 2012.
- Flannigan, M., Logan, K. A., Amiro, B. D., Skinner, W. R., and Stocks, B. J.: Future area burned in Canada, *Climatic Change*, 72, 1–16, 2005.
- Flannigan, M. D., Krawchuk, M. A., de Groot, W. J., Wotton, B. M., and Gowman, L. M.: Implications of changing climate for global wildland fire, *Int. J. Wildland Fire*, 2009, 483–507, <https://doi.org/10.1071/wf08187>, 2009.
- Giglio, L., Randerson, J. T., and van der Werf, G. R.: Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4), *J. Geophys. Res.-Biogeol.*, 118, 317–328, 2013.
- Granier, C., Bessagnet, B., Bond, T., D'Angiola, A., van der Gon, H. D., Frost, G. J., Heil, A., Kaiser, J. W., Kinne, S., Klimont, Z., Kloster, S., Lamarque, J. F., Liousse, C., Masui, T., Meleux, F., Mieville, A., Ohara, T., Raut, J.-C., Riahi, K., Schultz, M. G., Smith, S. J., Thompson, A., von Aardenne, J., van der Werf, G. R., and Vuuren, D. P.: Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980–2010 period, *Climatic Change*, 109, 163–190, 2011.
- Guyette, R. P., Muzika, R. M., and Dey, D. C.: Dynamics of an anthropogenic fire regime, *Ecosystems*, 5, 472–486, 2002.
- Haikerwal, A., Akram, M., Del Monaco, A., Smith, K., Sim, M. R., Meyer, M., Tonkin, A. M., Abramson, M. J., and Dennekamp, M.: Impact of fine particulate matter (PM_{2.5}) exposure during wildfires on cardiovascular health outcomes, *J. Am. Heart Assoc.*, 4, e001653, <https://doi.org/10.1161/JAHA.114.001653>, 2015.
- Hurt, G. C., Chini, L. P., Frothing, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Goldewijk, K. K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D. P., and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, *Climatic Change*, 109, 117–161, 2011.
- IEA: Energy Technology Perspectives 2012, International Energy Agency, Paris, 690 pp., 2012.
- Jacob, D. J. and Winner, D. A.: Effect of climate change on air quality, *Atmos. Environ.*, 43, 51–63, 2009.
- Jaffe, D., Chand, D., Hafner, W., Westerling, A., and Spracklen, D.: Influence of fires on O₃ concentrations in the western US, *Environ. Sci. Technol.*, 42, 5885–5891, 2008.
- Jaffe, D. A. and Wigder, N. L.: Ozone production from wildfires: a critical review, *Atmos. Environ.*, 51, 1–10, 2012.
- Jiang, L.: Internal consistency of demographic assumptions in the shared socioeconomic pathways, *Popul. Environ.*, 35, 261–285, 2014.
- Jiang, L. and O'Neill, B. C.: Global urbanization projections for the Shared Socioeconomic Pathways, *Global Environ. Chang.*, 42, 193–199, 2017.
- Kaiser, J. W., Heil, A., Andreae, M. O., Benedetti, A., Chubarova, N., Jones, L., Morcrette, J.-J., Razinger, M., Schultz, M. G., Suttie, M., and van der Werf, G. R.: Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power, *Biogeosciences*, 9, 527–554, <https://doi.org/10.5194/bg-9-527-2012>, 2012.

- Kajii, Y., Kato, S., Streets, D. G., Tsai, N. Y., Shvidenko, A., Nilsson, S., McCallum, I., Minko, N. P., Abushenko, N., and Altyntsev, D.: Boreal forest fires in Siberia in 1998: Estimation of area burned and emissions of pollutants by advanced very high resolution radiometer satellite data, *J. Geophys. Res.-Atmos.*, 107, 4745, <https://doi.org/10.1029/2001JD001078>, 2002.
- Kelley, D. I. and Harrison, S. P.: Enhanced Australian carbon sink despite increased wildfire during the 21 century, *Environ. Res. Lett.*, 9, 104015, <https://doi.org/10.1088/1748-9326/9/10/104015>, 2014.
- Klein Goldewijk, K., Beusen, A., and Janssen, P.: Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1, *Holocene*, 20, 565–573, 2010.
- Klimont, Z., Smith, S. J., and Cofala, J.: The last decade of global anthropogenic sulfur dioxide: 2000–2011 emissions, *Environ. Res. Lett.*, 8, 014003, <https://doi.org/10.1088/1748-9326/8/1/014003>, 2013.
- Kloster, S., Mahowald, N. M., Randerson, J. T., Thornton, P. E., Hoffman, F. M., Levis, S., Lawrence, P. J., Feddes, J. J., Oleson, K. W., and Lawrence, D. M.: Fire dynamics during the 20th century simulated by the Community Land Model, *Biogeosciences*, 7, 1877–1902, <https://doi.org/10.5194/bg-7-1877-2010>, 2010.
- Knorr, W., Lehsten, V., and Arneth, A.: Determinants and predictability of global wildfire emissions, *Atmos. Chem. Phys.*, 12, 6845–6861, <https://doi.org/10.5194/acp-12-6845-2012>, 2012.
- Knorr, W., Kaminski, T., Arneth, A., and Weber, U.: Impact of human population density on fire frequency at the global scale, *Biogeosciences*, 11, 1085–1102, <https://doi.org/10.5194/bg-11-1085-2014>, 2014.
- Knorr, W., Jiang, L., and Arneth, A.: Climate, CO₂ and human population impacts on global wildfire emissions, *Biogeosciences*, 13, 267–282, <https://doi.org/10.5194/bg-13-267-2016>, 2016a.
- Knorr, W., Arneth, A., and Jiang, L.: Demographic controls of future global fire risk, *Nat. Clim. Change*, 6, 781–785, <https://doi.org/10.1038/NCLIMATE2999>, 2016b.
- Knorr, W., Dentener, F., Hantson, S., Jiang, L., Klimont, Z., and Arneth, A.: Air quality impacts of European wildfire emissions in a changing climate, *Atmos. Chem. Phys.*, 16, 5685–5703, <https://doi.org/10.5194/acp-16-5685-2016>, 2016c.
- Krawchuk, M. A., Moritz, M. A., Parisien, M. A., Van Dorn, J., and Hayhoe, K.: Global pyrogeography: the current and future distribution of wildfire, *Plos One*, 4, e5102, <https://doi.org/10.1371/journal.pone.0005102>, 2009.
- Lamarque, J.-F., Emmons, L. K., Hess, P. G., Kinnison, D. E., Tilmes, S., Vitt, F., Heald, C. L., Holland, E. A., Lauritzen, P. H., Neu, J., Orlando, J. J., Rasch, P. J., and Tyndall, G. K.: CAM-chem: description and evaluation of interactive atmospheric chemistry in the Community Earth System Model, *Geosci. Model Dev.*, 5, 369–411, <https://doi.org/10.5194/gmd-5-369-2012>, 2012.
- Langmann, B., Duncan, B., Textor, C., Trentmann, J., and van der Werf, G. R.: Vegetation fire emissions and their impact on air pollution and climate, *Atmos. Environ.*, 43, 107–116, 2009.
- Lee, K. H., Kim, J. E., Kim, Y. J., Kim, J., and von Hoyningen-Huene, W.: Impact of the smoke aerosol from Russian forest fires on the atmospheric environment over Korea during May 2003, *Atmos. Environ.*, 39, 85–99, 2005.
- Lehsten, V., Harmand, P., Palumbo, I., and Arneth, A.: Modelling burned area in Africa, *Biogeosciences*, 7, 3199–3214, <https://doi.org/10.5194/bg-7-3199-2010>, 2010.
- Marlier, M. E., DeFries, R. S., Kim, P. S., Gaveau, D. L. A., Koplitz, S. N., Jacob, D. J., Mickley, L. J., Margono, B. A., and Myers, S. S.: Regional air quality impacts of future fire emissions in Sumatra and Kalimantan, *Environ. Res. Lett.*, 10, 054010, <https://doi.org/10.1088/1748-9326/10/5/054010>, 2015.
- Marlon, J. R., Bartlein, P. J., Carcaillet, C., Gavin, D. G., Harrison, S. P., Higuera, P. E., Joos, F., Power, M. J., and Prentice, I. C.: Climate and human influences on global biomass burning over the past two millennia, *Nat. Geosci.*, 1, 697–702, 2008.
- Monks, P. S., Granier, C., Fuzzi, S., Stohl, A., Williams, M., Akimoto, H., Amann, M., Baklanov, A., Baltensperger, U., and Bey, I.: Atmospheric composition change – global and regional air quality, *Atmos. Environ.*, 43, 5268–5350, 2009.
- Page, S. E., Siebert, F., Rieley, J., Boehm, H.-D., Jayak, A., and Limink, S.: The amount of carbon released from peat and forest fires in Indonesia during 1997, *Nature*, 420, 61–65, 2002.
- Prestele, R., Alexander, P., Rounsevell, M. D. A., Arneth, A., Calvin, K., Doelman, J., Eitelberg, D. A., Engström, K., Fujimori, S., and Hasegawa, T.: Hotspots of uncertainty in land-use and land-cover change projections: a global-scale model comparison, *Global Change Biol.*, 22, 3967–3983, 2016.
- Randerson, J., Chen, Y., van der Werf, G. R., Rogers, B. M., and Morton, D. C.: Global burned area and biomass burning emissions from small fires, *J. Geophys. Res.*, 117, G04012, <https://doi.org/10.1029/2012JG002128>, 2012.
- Rao, S., Klimont, Z., Leitao, J., Riahi, K., van Dingenen, R., Reis, L. A., Calvin, K., Dentener, F., Drouet, L., and Fujimori, S.: A multi-model assessment of the co-benefits of climate mitigation for global air quality, *Environ. Res. Lett.*, 11, 124013, <https://doi.org/10.1088/1748-9326/11/12/124013>, 2016.
- Shindell, D. T., Lamarque, J.-F., Schulz, M., Flanner, M., Jiao, C., Chin, M., Young, P. J., Lee, Y. H., Rotstayn, L., Mahowald, N., Milly, G., Faluvegi, G., Balkanski, Y., Collins, W. J., Conley, A. J., Dalsoren, S., Easter, R., Ghan, S., Horowitz, L., Liu, X., Myhre, G., Nagashima, T., Naik, V., Rumbold, S. T., Skeie, R., Sudo, K., Szopa, S., Takemura, T., Voulgarakis, A., Yoon, J.-H., and Lo, F.: Radiative forcing in the ACCMIP historical and future climate simulations, *Atmos. Chem. Phys.*, 13, 2939–2974, <https://doi.org/10.5194/acp-13-2939-2013>, 2013.
- Shu, L., Tian, X., and Wang, M.: A study on forest fire occurrence in China, XII World Forestry Congress, Québec City, Canada, 21–28 September, available at: <http://www.fao.org/docrep/ARTICLE/WFC/XII/0278-B1.HTM> (last access: 26 July 2017), 2003.
- Silva, R. A., West, J. J., Zhang, Y., Anenberg, S. C., Lamarque, J.-F., Shindell, D. T., Collins, W. J., Dalsøren, S. B., Faluvegi, G., Horowitz, L. W., Nagashima, T., Naik, V., Rumbold, S., Skeie, R., Sudo, K., Takemura, T., Bergmann, D., Cameron-Smith, P., Cionni, I., Doherty, R. M., Eyring, V., Joesse, B., MacKenzie, I. A., Plummer, D., Righi, M., Stevenson, D. S., Strode, S., Szopa, S., and Zeng, G.: Global premature mortality due to anthropogenic outdoor air pollution and the contribution of past climate change, *Environ. Res. Lett.*, 8, 034005, <https://doi.org/10.1088/1748-9326/8/3/034005>, 2013.
- Silva, R. A., West, J. J., Lamarque, J.-F., Shindell, D. T., Collins, W. J., Dalsøren, S., Faluvegi, G., Folberth, G.,

- Horowitz, L. W., Nagashima, T., Naik, V., Rumbold, S. T., Sudo, K., Takemura, T., Bergmann, D., Cameron-Smith, P., Cionni, I., Doherty, R. M., Eyring, V., Josse, B., MacKenzie, I. A., Plummer, D., Righi, M., Stevenson, D. S., Strode, S., Szopa, S., and Zeng, G.: The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble, *Atmos. Chem. Phys.*, 16, 9847–9862, <https://doi.org/10.5194/acp-16-9847-2016>, 2016.
- Smith, B., Prentice, C., and Sykes, M.: Representation of vegetation dynamics in modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space, *Global Ecol. Biogeogr.*, 10, 621–637, 2001.
- Sofiev, M., Ermakova, T., and Vankevich, R.: Evaluation of the smoke-injection height from wild-land fires using remote-sensing data, *Atmos. Chem. Phys.*, 12, 1995–2006, <https://doi.org/10.5194/acp-12-1995-2012>, 2012.
- Spracklen, D. V., Mickley, L. J., Logan, J. A., Hudman, R. C., Yevich, R., Flannigan, M. D., and Westerling, A. L.: Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States, *J. Geophys. Res.-Atmos.*, 114, D20301, <https://doi.org/10.1029/2008JD010966>, 2009.
- Stohl, A., Aamaas, B., Amann, M., Baker, L. H., Bellouin, N., Berntsen, T. K., Boucher, O., Cherian, R., Collins, W., Daskalakis, N., Dusinska, M., Eckhardt, S., Fuglestvedt, J. S., Harju, M., Heyes, C., Hodnebrog, Ø., Hao, J., Im, U., Kanakidou, M., Klimont, Z., Kupiainen, K., Law, K. S., Lund, M. T., Maas, R., MacIntosh, C. R., Myhre, G., Myriokefalitakis, S., Olivie, D., Quaas, J., Quennehen, B., Raut, J.-C., Rumbold, S. T., Samset, B. H., Schulz, M., Seland, Ø., Shine, K. P., Skeie, R. B., Wang, S., Yttri, K. E., and Zhu, T.: Evaluating the climate and air quality impacts of short-lived pollutants, *Atmos. Chem. Phys.*, 15, 10529–10566, <https://doi.org/10.5194/acp-15-10529-2015>, 2015.
- Su, L., He, Y., and Chen, S.: Temporal and spatial characteristics and risk analyses of forest fires in China from 1950 to 2010, *Scientia Sinicae*, 51, 88–96, 2015.
- Syphard, A. D., Radeloff, V. C., Keeley, J. E., Hawbaker, T. J., Clayton, M. K., Stewart, S. I., and Hammer, R. B.: Human influence on California fire regimes, *Ecol. Appl.*, 17, 1388–1402, 2007.
- Tai, A. P. K., Mickley, L. J., and Jacob, D. J.: Correlations between fine particulate matter (PM_{2.5}) and meteorological variables in the United States: implications for the sensitivity of PM_{2.5} to climate change, *Atmos. Environ.*, 44, 3976–3984, 2010.
- Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An overview of CMIP5 and the experiment design, *B. Am. Meteorol. Soc.*, 93, 485–498, 2012.
- Tilmes, S., Lamarque, J.-F., Emmons, L. K., Kinnison, D. E., Marsh, D., Garcia, R. R., Smith, A. K., Neely, R. R., Conley, A., Vitt, F., Val Martin, M., Tanimoto, H., Simpson, I., Blake, D. R., and Blake, N.: Representation of the Community Earth System Model (CESM1) CAM4-chem within the Chemistry-Climate Model Initiative (CCMI), *Geosci. Model Dev.*, 9, 1853–1890, <https://doi.org/10.5194/gmd-9-1853-2016>, 2016.
- Tsyro, S. G.: To what extent can aerosol water explain the discrepancy between model calculated and gravimetric PM₁₀ and PM_{2.5}?, *Atmos. Chem. Phys.*, 5, 515–532, <https://doi.org/10.5194/acp-5-515-2005>, 2005.
- van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), *Atmos. Chem. Phys.*, 10, 11707–11735, <https://doi.org/10.5194/acp-10-11707-2010>, 2010.
- van der Werf, G. R., Peters, W., van Leeuwen, T. T., and Giglio, L.: What could have caused pre-industrial biomass burning emissions to exceed current rates?, *Clim. Past*, 9, 289–306, <https://doi.org/10.5194/cp-9-289-2013>, 2013.
- van Vuuren, A. J., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F., Masui, T., Meinshausen, M., Naicenovic, N., Smith, S. J., and Rose, S. K.: The representative concentration pathways: an overview, *Climatic Change*, 109, 5–31, 2011.
- Veira, A., Kloster, S., Wilkenskjaed, S., and Remy, S.: Fire emission heights in the climate system – Part I: Global plume height patterns simulated by ECHAM6-HAM2, *Atmos. Chem. Phys.*, 15, 7155–7171, <https://doi.org/10.5194/acp-15-7155-2015>, 2015.
- Wang, Z., Chappellaz, J., Park, K., and Mak, J. E.: Large variations in Southern Hemisphere biomass burning during the last 650 years, *Science*, 330, 1663–1666, 2010.
- West, J. J., Smith, S. J., R1 Silva, A., Naik, V., Zhang, Y., Adelman, Z., M. M. Fry, Anenberg, S., Horowitz, L. W., and Lamarque, J.-F.: Co-benefits of global greenhouse gas mitigation for future air quality and human health, *Nat. Clim. Change*, 3, 885–889, <https://doi.org/10.1038/nclimate2009>, 2013.
- WHO: Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, Global update 2005, Summary of risk assessment, World Health Organization, Geneva, Switzerland, 2006.
- Yue, X., Mickley, L. J., Logan, J. A., and Kaplan, J. O.: Ensemble projections of wildfire activity and carbonaceous aerosol concentrations over the western United States in the mid-21 century, *Atmos. Environ.*, 77, 767–780, 2013.
- Yue, X., Mickley, L., Logan, J., Hudman, R., Martin, M. V., and Yantosca, R.: Impact of 2050 climate change on North American wildfire: consequences for ozone air quality, *Atmos. Chem. Phys.*, 15, 10033–10055, <https://doi.org/10.5194/acp-15-10033-2015>, 2015.