<u>Reply to referee comments to “Wildfire air pollution hazard during the 21st century” by Knorr et al.</u>

Report #1, Anonymous Referee #3

This manuscript presents a study on the effects of humans and climate on fire activity and consequences for air pollution across the 21 century. The Authors use LPJ-GUESS with SIMFIRE to produce a set of future fire emissions (based on GFED4s for present-day) and the chemical transport model CAM-Chem to study air quality impacts. The effect of climate and human intervention on future fire activity and air pollution is an important topic and results from this work are of relevant interest for the readers of the ACP. This manuscript is a revised version of a previously submitted manuscript. However, despite the substantial work done by the Authors to address the reviewers' comments, I find the manuscript still very confusing and poorly organized and cannot be published as it is.

Following the comments of Referee #3, as well as Referee #2 and the editor, we substantially revised the structure of the manuscript such that it now focuses on one point, the possible impact of wildfires on the ability to meet WHO air quality guidelines for PM2.5 by the WHO. The guiding question is now “*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.*”, stated in the (new) last paragraph of Section 1. Section 3 (Results) has been completely re-written, with the assessment of current emission levels dropped (former Fig. 1 is now included in the SI as part of Fig. S1) and the number of subsections reduced to two, one for pollutant emissions and one for pollutant concentrations. A new paragraph has been added at the beginning of Section 4 (Discussion) that summarizes the impact of different scenarios on human pollutant exposure, as well as a discussion of a possible WHO target for monthly mean concentrations that would be expected to lie somewhere between the annual and daily mean value. Section 5 (Summary and conclusions) has been shortened to contain only the main three points.

The PM2.5 concentrations simulated with CAM-Chem using the SIMFIRE fire emissions are key in the revised manuscript. However, this additional analysis does not blend within the manuscript and is missing important information. For example, CAM-Chem does not provide directly PM2.5 as an output, what species did the Authors consider to calculate PM2.5?

This was indeed stated in Section 2.2, 3rd paragraph of the previous revision in the following sentence: “*The computed seasonal cycle of emissions of CO, NH3, SO2, NOx, 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. 2010)*“

We have now added text to Section 2.2 (line 220, after Equ. 4 and after the now revised sentence shown above) to better provide more detail on this procedure.

The Authors do not discuss how well CAM-Chem represents PM2.5 (without seasalt and dust). My understanding is that Tilmes et al (2016) does not evaluate PM2.5, rather individual PM2.5 species. The simulations planned with CAM-Chem are not clear until the reader gets to the results. I understand that there were some computing time constrains. However, air quality simulations are typically performed for at least 10 years to consider any interannual climate variability. Also, the Authors could have run a simulation without fires in 2090 to determine the delta PM2.5 from fires.

PM2.5 is indeed computed as the collection of all individual aerosol components (SO4, NO3, NH4, OM and BC), and limited to mostly fire and anthropogenic aerosol. As such, dust and sea-salt were not added to PM2.5, as they are typically very uncertain, and limited to regions where unfortunately not many observations are available. Simulations were limited to 25 months, due to the particular model set-up, large internal variability was avoided, and small compared to the change in emissions and therefore did not warrant longer simulations. Although we did not show this in the manuscript, this information was derived from the 25-month simulations. The last paragraph of Section 2.3 has be extended substantially with a review of available validation of CAM-Chem.

The manuscript seems to be written in patches and gives the impression that the unnecessary figures from the previous version were moved to supplementary materials. For example, the paper shows first results from wildfires, peat and deforestation fires with the SSP2, SSP3 and SSP5 and RCP4.5 and RCP8.5 scenarios for 2000-2100 (Supplementary Materials). Then, it shows wildfire PM2.5 emissions against population for SSP3/RCP45&CLE and SSP5/RCP85&MFR for 2010, 2030, 2050 and 2090. Why aren't deforestation and peat fire emissions included in the analysis here? Finally, it presents PM2.5 concentrations from CAM-Chem for 2010 and 2090 for SSP3/RCP45-CLE, SSP3/RCP45-CLE and SSP5/RCP85-MFR. Again here, only wildfire emissions are considered. Can the Authors identify the key points they want to show and remove the rest?

An analysis of the magnitude of emissions from peat and deforestation fires was included in the previous revision in order to check if they are a major contribution, and if yes where. We concluded that they were not and laid this out in the manuscript. After that the manuscript proceeded without those sources for two reasons: 1) They are relevant now mostly in Indonesia because only there they occur in a region with high population densities, 2) they are difficult to project into the future. We then focussed on wildfires which are to a large extent outside the reach of policy measures, witnessed by the futility of fire suppression measures as discussed in the (new and old) text.

In the revised version, we have streamlined the presentation and focus in particular on this difference between wildfire emissions (difficult to control by policy) and anthropogenic emissions (now a routine target of policy intervention). We now only show emissions for a total of four future scenarios (summarized in a new Table 1) and only for 2090, not for 2030 or 2050 as in the previous revision. As was shown in previous publications, by 2090 we expect a substantial change in wildfire emissions and thus maximize their potential to interfere with policy targets.

Of the four future scenarios, three are fed to CAM-Chem for simulations of pollutant concentrations. Table 1 also lists two scenario differences that can be used to assess the importance of the wildfire vs. anthropogenic emissions scenarios, and these are then used to guide the analysis and discussion. Further, a guiding question is developed and explained at the end of Section 1 (Introduction) and again further explain in a new paragraph at the end of Section 2.3. The results section has been re-written to follow this guidance. We hope that this improves readability and creates are more coherent narrative for the manuscript.

One important result is the % of people that will be exposed to PM2.5 levels above the WHO air quality standard (10 ug/m3) as a result of fire pollution. The Authors show these results in Figure 5 and Table 2. I may be missing something in the analysis, but in Fig. 5 I do not see any population range with PM2.5 levels above 10 ug/m3, except for Asia. Also, over Sub-Sahara Africa and Middle East PM2.5 concentrations are typically dominated by dust and this emission source is not considered. Over these regions, a small influence of fire pollution may make population be exposed to PM2.5 levels > 10 ug/m3.

After careful consideration, we decided to drop the analysis of number of people exposed to dangerous levels of PM2.5 following the new focus on monthly exposure levels. Since there is no agreed air quality guidance for monthly mean PM2.5, the number of people exposed becomes very strongly dependent on the finally agreed value (something that was checked but is not shown). We therefore decided to restrict the analysis to main concentrations in population-density bands, which also helped further streamlining the manuscript, but also added a new figure showing annual mean in addition to monthly PM2.5.

This figure with annual mean PM2.5 should also reveal that averages over all areas with certain ranges of population density (shown in Fig. 3, previously Fig. 5) can mask regional differences with high values (new Fig. 4). We also added a discussion pointing out that smaller-scale urban areas with high population densities may have exposure levels that are not shown due to the fact that the highest category starts at a lower levels (line 381). We did not include a separate category for those very high population densities because wildfires are much less relevant for urban pollution, so that this is not the focus of the present study.

We do state that mineral dust or sea salt were excluded because they do not interact with the formation of aerosols from biomass burning (line 226). We also extensively discuss several limitations of the present work and recommendations for further studies, including consideration of mineral dust (e.g. line 380) in Section 4.

Some additional notes:

PM2.5 is PM$_{2.5}$.

Has been corrected throughout.

Spracklen et al. (2009) and Yue et al. (2013) were the first studies to examine PM2.5 impacts from future wildfires. These results should be referenced. Val Martin et al. (2015) also showed future PM2.5 changes as a result of fires with CAM-Chem.

We have added these references, except for Val Martin et al. (2015) as this is a different focus (no prediction of future $PM_{2.5}$ levels).

Line 200. The Authors should cite Lamarque et al. (2012), instead of (2010).

Done.

Line 240-241 Why were the simulations done at 1 deg and the analysis at 1/2 deg? It does not make sense to me to increase resolution if the bulk fire emissions are at 1 deg.

Population density detail enters the calculations at ½ degree and affects for example the exposure calculations in Table 2. We have added a statement explain that doing the final analysis at a higher resolution helps with accounting for the impact of socio-economic factors on wildfire activity (line 168).

Line 324. I don't see how SIMFIRE differs from GFED4s in Figures S5 and S6.

We are not sure what the reviewer is referring to; Figs. S5 and S6 of the previous version show SIMFIRE simulations without anomaly correction, so GFED4s does not enter these results. These figures have new been removed.

Figure 3. I find a bit odd that changes in annual PM2.5 emissions wrt population in Sub-Sahara Africa and South&Southeast Asia are very similar or even identical. These two regions are different in terms of fire regimes, anthropogenic emissions and population, correct?

There was an error here, thank you for spotting this! This figure has been removed to further focus the manuscript.

Report #2, Anonymous Referee #2

In this paper, the authors use a dynamic vegetation model to probe the response of global wildfires to changes in climate and the CO2 content of the atmosphere. While warmer temperatures from climate change will likely lead to increased wildfire activity in much of the world, increasing CO2 concentrations could affect vegetation in ways that could diminish that activity. The paper also seeks to compare future concentrations of wildfire PM2.5 to those of anthropogenic PM2.5, and in some places the authors find that wildfire emissions will dominate pollution sources. The paper further compares the trends of future wildfire emissions and area at different population densities.
The main update from the first version of this paper seems to be the use of chemistry model to represent concentrations of PM2.5 in the present-day and future (2090s) atmosphere.

We agree that this is a good summary.

The key points of the paper seem to be as follows:

A. Present-day wildfires in some developing countries are greatest in regions of intermediate density (1-100 people km-2).

This is not a new result (e.g. Knorr et al. 2016b, Nature Climate Change), but perhaps the manuscript did leave this impression. We have reduced the number of figures showing emissions against ranges of population density from two to one, and streamlined the results and summary significantly to make this (hopefully) much clearer.

In this study, we have taken up the analysis by population density ranges again, because we believe that highlighting the linkage between wildfire on the one hand, and anthropogenic emissions on the other to population density is an interesting approach. This is because (1) the analysis clearly shows that most anthropogenic emissions are driven by population density (which is not self-evident, considering emissions from agricultural burning, transport, exploration activities etc.), but also that population density is a main driver for wildfire emissions linked to developments in rural population, but with distinctly different but often unexpected patterns; and (2) population density in polluted areas is highly relevant for policy.

B. Under some scenarios, the CO2 fertilization effect increases shrub, and so there is less fire. This appears to matter most in Sub-Saharan Africa.

This has been shown and discussed extensively in Knorr et al. 2016a (Biogeosciences). However, it is only discussed in the introduction, so we are not sure why the referee lists it here.

C. In the slow-urbanization scenario in some regions – e.g., Australia – more people move into fire-prone areas and so more people are exposed to greater fire emissions.

This has also been discussed much more in Knorr et al. (2016a,b). Because the newly revised manuscript focuses more on concentrations and leaves out detailed comparison of urbanisation effects, it is now off-scope, but not a new result anyway.

D. In the Maximum Feasible Reduction scenario, in which anthropogenic emissions decline the most, wildfires emissions will dominate over anthropogenic emissions in many regions, especially in China and Southeast Asia, and parts of Africa and South America

This is indeed the main result. We refer to this in more general terms in a new paragraph at the start of Section 4 (Discussion) and in more detail in the following paragraph. The point made by the reviewer is also referred to by two of the remaining three bullet points of the summary (Section 5).

Main points.

1. The paper is very difficult to read, and discerning the main points is challenging. Much of the paper rambles, and the assistance of a really good editor is needed. The use of cumbersome acronyms is especially confusing – e.g., one scenario is called CLE/SSP5/RCP8.5, and another one is called MFR/SSP5/RCP8.5.

We hope that this has improved considerably by concentrating on just four scenarios, combining CLE and MFR on the one hand with SSP5/RCP8.5 and SSP3/RCP4.5 on the other (four combinations in total, which are listed in a new Table 1). We also tried to help the reader by frequently referring to SSP5/RCP8.5 as the high wildfire emissions scenario and to SSP4/RCP4.5 as the low wildfire emissions scenario. In addition, we considerably revised Section 2.2 of the methods in order to better describe the method used to calculate the final emissions fields.

2. The main goal of the paper appears to be to determine whether wildfires will affect our ability to meet WHO air quality guidelines. But it's very difficult to determine from the current set of figures where wildfires would pose such a challenge. See points #3 and #4.

We did not include a simulation with only wildfire pollutant sources, but rather assess the importance of differences between wildfire scenarios at a scenario of very low anthropogenic emissions. The regions where wildfires matter can thus be seen in Fig. 5 for peak-month, and the new Fig. 4 for annual mean concentrations by comparing different scenarios. Text has been added to the last paragraph of Section 3.2 that describes the regions that stand out as being largely influenced by wildfire emissions (line 425): "*For all scenarios, large sparsely populated regions in central South*

America, northeastern Siberia and northwestern Canada experience monthly pollution levels in excess of 10µg/m³ and to a lesser extent 25 µg/m³. This result is largely independent of the anthropogenic-emissions scenario (comparing Fig. 5b with 5c, d). In regions that show large reductions of annual mean pollution levels for MFR, monthly maximum concentrations can still substantially surpass 10 µg / m³ even under an MFR scenario (Africa, Southeast Asia and, to some extent for SSP5/RCP8.5, south-eastern China), or even 25 µg m⁻³ (Africa, South-East Asia)."

Besides, a simulation with only fire sources poses some theoretical issues, as we may run into non-linear responses. It is not impossible but beyond the scope of this paper.

3. The figures contain more information than is needed, obscuring the main points. For example, it appears we are meant to compare the dashed lines in Figures 3 and 4. These lines represent wildfire emissions for different timeslices at different population densities in different regions for different scenarios. But these differences across cases seem very small on the page, and are nearly nonexistent in some cases. The use of log-scales makes it even more difficult to compare fire activity across regions, and the very tiny values in some regions (e.g., the Middle East) seem not worth showing. In well-composed figures, the main messages pop out at the reader, but that doesn't happen here. The plots should be carefully designed to illustrate the main points of the paper. More detailed plots should be relegated to the Supplement.

We have streamlined the results section by removing time slices that were not used for the CAM-Chem simulations. In the newly revised version, the results section is now guided by the question of which emissions are higher as one requisite for the importance (Fig. 1), if they occur close to population for a scenario selected from Fig. 1 (Fig. 2), how emissions relate to concentrations (Fig. 3), how concentrations relate to population patterns (Fig. 3), and finally identification of regions where each source matters (Figs. 4 and 5). Fig. 5 shows peak-month concentrations, as a conclusion from the findings of Fig. 4. We believe that this new choice of figures constitutes a much better and more coherent story.

4. More issues with figures. The plots show annual emissions of PM2.5, but of course wildfire has strong seasonal peaks. In this way, the plots are misleading. Also misleading is the apparent neglect of secondary organic aerosol (SOA) from biogenic emissions. By showing only emissions, Figure 1 implies that PM2.5 in the Amazon and the Southeast US is anthropogenic, but of course SOA dominates the aerosol burden in these regions. And SOA is expected to increase in the future atmosphere, due to the impact of rising temperatures on biogenic emissions. There is also inadequate treatment of dust. Figure 5 shows total PM2.5 and so it's unclear to what extent wildfires drive these concentrations.

Fig. 5 shows season-peak concentrations, but a newly added Fig. 4 shows annual mean concentrations, so we hope that it is now clearer that we do include seasonal variations. The impact of either anthropogenic or wildfire

emissions are seen by comparing different scenarios according to the newly added Table 1. For example, the difference between Fig. 4 or 5 b and d is due to the anthropogenic emissions scenario, while the difference between Fig. 4 or 5 c and d is due to the wildfire emissions scenario.

SOAs and biogenic volatile compounds were actually not ignored in the simulations (see line 239).

5. Perhaps the authors should just focus on a few key regions (or better subregions) and show not annual emissions but fire season concentrations for the present-day and 2090s at different population densities. The contributions of wildfires to total PM2.5 should be clearly denoted.

In principle, we agree with the referee that figures should convey the main message. However, we also believe that the main advantage of a full-format journal such as ACP is that readers can be guided through a narrative that presents the breadth of results, leading to intermediate conclusions that then guide further analysis. We have therefore retained some breadth with the comparison of anthropogenic vs. wildfire emissions, or the analysis of emissions vs. population density, of which not all enter the final analysis of simulated pollution levels. And we have retained the presentation of all global regions (with small exceptions). Fire-season concentrations enter Fig. 5.

6. The paper does not sufficiently reference previous papers – e.g., Pechony and Shindell (2010). This reviewer asked for this reference in the first review. Also, it is not true that wildfires will increase everywhere in the future climate: Yue et al. (2015) shows decreasing fires in the future climate in parts of Canada.

We did not include Pechony and Shindell 2010, because it simulated neither emissions nor burned area, but a measure of fire activity that is closer to number of fires, and less relevant for emissions than for example burned area. We did, however, add Yue et al. (2015) along with Yue et al. (2013).

Title:

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 CO_2, as well as 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

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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 emission have the potential to limit mean annual pollutant $PM_{2.5}$ levels to comply with WHO air quality guidelines for $PM_{2.5}$. Worse-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 by 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 un-managed) 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 micrometers ($PM_{2.5}$), 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

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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 sub-regions in northern Canada). However, a long-term increase in the length of the fire season or in weather conditions conducive of wildfires does not necessarily lead to increases in burned area (Doerr and Santin 2016). This is because, at longer time scales, vegetation responds not only to climate change, but also directly to rising atmospheric CO_2 levels (Buitenwerf et al. 2012, Donohue et al. 2013). While CO_2 fertilization will lead to increased fuel load, enhancing emissions, it 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.

Another factor that has 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

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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 not accounting for demographic changes (Kloster et al. 2010). Some studies showed even 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 urbanisation 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 emissions from wildfires on human society are also largely determined by population growth and their spatial distribution (Knorr et al. 2016 b). It is therefore important to consider not only climate and CO_2 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

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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). Shortly, 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 plant-functional-type (PFT) dependent probability. 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 then re-scaled using per-country relative growth in rural and urban population, retaining the urban masks of the HYDE data. Grid cells with more than

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50% past or future cropland area in either the RCP6.0 or 4.5 land use scenarios (Hurtt et al. 2011; see Section 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 (GFED 4, van der Werf et al. 2010, based mainly on Akagi et al. 2011, see http://www.falw.vu/~gwerf/GFED/GFED4), 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 emissions 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, respectively (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 moderate, and RCP8.5 with high degree of climate change. Simulations for 1901 to 2100 are carried out on a global equal-area grid with 1° x 1° 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 urbanisation projections following the Shared Socioeconomic 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

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range of socio-economic, demographic and biophysical factors. Here, we focus on two combinations that represent, respectively, 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 urbanisation 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 urbanisation 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 emissions fields for wildfires (van der Werf et al. 2010, updated using Randerson et al. 2012 and Giglio et al. 2013) aggregated to 0.5° x0.5° resolution and then re-scaled in time by country or region (following the methodology of Knorr et al. 2016c). For larger countries, scaling is done by sub-national regions, which were chosen in such a way as to isolate major fire areas found in GFED4.1s. (For a list of regions/countries, see Table S1 in the Supplementary Information). The use of country boundaries and performing the analysis at 0.5x0.5° 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

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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 of their regional importance mainly in Southeast-Asia (Fig. S1, Table S2)

In contrast to Knorr et al. (2016c), where changes in the spatial distribution of population within a country did not affect predicted wildfire emissions, here we also account for demographic effects at 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/country, with a scalar accounting for population effects, f_p, which is applied at each grid cell separately:

$$E^S(x,y,m) = f^S_{cv}(R(x),y) * f_p(\Delta p'(x,y)) * E^S_{GFED}(x,m) \qquad (1)$$

with E^S the re-scaled per-grid-cell emissions of chemical species S, x the geographic location on the 0.5°x0.5° grid used for the analysis, y year, m month of the year, $R(x)$ the country or region found at location x, and E^S_{GFED} the (per-grid-cell) emissions climatology of species S from GFED 4.1s averaged over 1997 to 2014. The population effect, f_p , is equal to the population multiplier of SIMFIRE (Knorr et al. 2016a):

$$f_p(\Delta p') = \exp(-0.0168*\Delta p'). \qquad (2)$$

with $\Delta p'(x,y)=p'(p(x,y))-p'(p(x,y_0))$, where $p'(p)$ is the minimum of population density p and 100 inhabitants per km^2. y_0=2010 is the reference year relative to which future emission levels are computed. 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 much above 100 / km^2. In other words, we consider areas with a

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population density above 100 / km^2 to be essentially wildfire free. The combined effect of climate and vegetation on emissions is defined as:

$$f^S_{cv}(R,y) = \{\Sigma_{x'\in R}\, E^S_{SIM}(x',y) \,/\, \Sigma_{x'\in R}\, E^S_{SIM}(x',y_0)\} \,/ \ldots$$

$$\ldots \{\Sigma_{x'\in R}\, f_p(p(x',y)-p(x',y_0))\, E^S_{GFED}(x',m) \,/\, \Sigma_{x'\in R}\, E^S_{GFED}(x',m)\}, \quad (3)$$

Here, E^S_{SIM} are LPJ-GUESS-SIMFIRE emissions of species S computed on the 1° equal-area grid. The sums are over all grid cells x' of the 1° equal-area grid that belong to region/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), which is divided by the projected change in emissions only due to changes in population density (second term in curly brackets; see Fig. S3 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:

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

Countries where 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 $f^S_{cv}(R,y)=f_p(p)=1$. 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, NH_3, SO_2, 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.,

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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 $E^S_{GFED}(x,m)$, and for 2090 emissions $E^S_{2090}(x,m)$ (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 x 1.25° longitude. The model has 26 vertical layers from the surface to approximately 40 km. CAM-Chem is here used as a chemical transport model, with the meteorology being the same between simulations with different emissions 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 mono-terpenes, 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 United States, indicating an overall good representation of the probability density function for all species considered in the present study. In

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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 impacts 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 interannual variability in the two 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 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 World Health Organization (WHO) air quality guidelines of 10 $\mu g/m^3$ 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 3–5 $\mu g\ m^{-3}$ 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 dataset provides two scenarios: current legislation (CLE), and maximum feasible reductions (MFR) on top of business-as-usual projections until 2050 from the Energy Technology Projections study by the International Energy Agency (IEA, 2012), which are considered roughly equivalent to RCP6.0. MFR corresponds to a policy and technology driven abatement scenario, implementing all currently known technologies at a reasonable cost, with the aim,

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among others, to lower $PM_{2.5}$ emissions to levels of 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 half of the corresponding 2050 levels (i.e. somewhat optimistic compared with e.g. Braspenning-Radu et al., 2016). 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 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). 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 & New Zealand, and North America. Countries of Europe belonging to the middle-incoming group were assigned to the region Eastern Europe and Central Asia, which also includes Russia. High-income countries of the Middle East (Israel, oil-rich states of the Persian Gulf) or East Asia (Japan, 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 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 µg / m^3, under a scenario in which

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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 emissions 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

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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. Fig. 1 shows areas where wildfire emissions currently exceed those from anthropogenic sources (in either red or light blue; shown in all panels). At first sight, these regions appear to lie in relatively remote areas of wildfire-prone regions (cf. Fig. S5, e.g. the boreal forest zones of Canada and Alaska, eastern Siberia, 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 (cf. Fig. S4) 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 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 highest per-area emissions in some intermediate population-density category, and it is not the most remote and sparsely inhabitated areas that have the highest emissions. Therefore, despite of a dominance of anthropogenic emissions in the more densely populated areas, wildfires 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 10 to 100 / km^2 (Sub-Saharan Africa, Latin America & Caribbean, South & Southeast Asia, Australia & New Zealand). This 10 to 100 / km^2 category is significant not only because of its relatively high population 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, 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, Southeast Asia, and southern China). This dominant role of the anthropogenic-emissions scenario is largely independent of the wildfire emissions scenario (i.e. the difference between Fig. 1a and b or between Fig. 1b and d is much small than the difference between Fig. 1a, b on the one hand and Fig. 1 c, d on the other). The strongest impact of the wildfire emissions scenario is found for Sub-Saharan Africa for the CLE scenario, where 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). The scenario in which wildfire emissions are most likely to become a relevant source of $PM_{2.5}$ emissions is represented by the combination MFR/SSP5/RCP8.5 (Fig. 1d and Fig. 2, red lines; cf. also Fig. S2b).

The MFR scenario assumes a decline in anthropogenic emissions by approximately one 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/RC8.5 is much smaller throughout. The highest absolute increase for wildfire emissions is found for Sub-Saharan Africa (in the 1 to 100 / km^2 categories), Latin America (0.1 to 1 / km^2), South & Southeast 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 / km^2) for Sub-Saharan Africa, Latin America & Caribbean, Eastern Europe-Russia-Central Asia, South & Southeast Asia and Australia & New Zealand. Note that the areas of the population density categories shift as well (see dotted lines in Fig. 2 and Fig. S5), and that the underlying population patterns used to compute the MFR scenario do not necessarily match those from SSP5.

3.3 Changing patterns of $PM_{2.5}$ pollutant exposure

Simulated changes of $PM_{2.5}$ concentrations between current and 2090 for the high-wildfire emissions scenario combined with MFR (Fig. 3 blue to red line, corresponding to emissions of Fig. 2, same colours) indicate a reduction in $PM_{2.5}$ pollutant concentration by between one half and three-quarters in the most densely

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populated category (>100 / 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 µg / m^3 (Developing East Asia, South & Southeast Asia; note the different axis scales), and none 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 Figs. 2 and 3 small areas with typical urban population densities e.g. above 1000 / km^2 are included in same category in 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 $PM_{2.5}$ 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 in Fig. 3), for 2090 concentrations peak at an intermediate level of population density in most regions (red line: Sub-Saharan Africa, Latin America & Caribbean, Eastern Europe-Russia-Central Asia, Australia & New Zealand, 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 $PM_{2.5}$ emissions by 2090 (Fig. 2, red lines).

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

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green lines in Fig. 3, cf. 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 emissions scenario, the effect of the wildfire scenario (difference between high and low wildfire-emissions scenario, red and light-blue lines in Fig. 3) is relatively small and only visible in Sub-Saharan Africa, South & South-East Asia and Developing East Asia.

Simulated spatial patterns of $PM_{2.5}$ concentrations for current conditions as well as for the CLE scenario (Fig. 4 a, b) show large parts of central Africa as well as most of South, East and Southeast Asia with concentrations above the WHO air quality guidance value. For MFR (Fig. 4c, d), however, only limited areas in central Africa show levels exceeding 10 µg / 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 areas are much more sparsely populated (see Fig. S4). 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 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 $PM_{2.5}$ 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-hour means that amount to 25 µg m^{-3}. We here assume that formally declared safe monthly $PM_{2.5}$

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concentrations would be somewhere between 10 and 25 µg m^{-3}. When investigating monthly $PM_{2.5}$ concentrations, the picture changes considerably. For all scenarios, large but sparsely populated regions in central South America, northeastern Siberia and northwestern Canada (cf. Fig. S5) experience monthly pollution levels in excess of 10 µg / m^{3} (Fig. 5) and to a lesser extent 25 µg / m^{3}. This result is largely independent of the anthropogenic-emissions scenario (comparing Fig. 5b with 5c, d). In regions that show large reductions of annual mean pollution levels for MFR, monthly maximum concentrations can still substantially surpass 10 µg / m^{3} even under an MFR scenario (Africa, Southeast Asia and, to some extent for SSP5/RCP8.5, south-eastern China), or even 25 µg m^{-3} (Africa, South-East Asia). 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 µg / m^{3} annual mean $PM_{2.5}$ 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 of the highest pollution levels away from the most densely populated areas, which reduces the impacts of future human exposure to $PM_{2.5}$. 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

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therefore find many regions where pollution levels can reach dangerous levels even for a scenario of aggressive reduction of anthropogenic emissions.

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 an RCP 4.5 and 8.5 scenario, 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 urbanisation and population decline in rural areas. While forest fires in China may have received comparatively little attention, they can still be substantial, with over 670,000 ha area burnt annually between 1950 and 2010 (Shu et al. 2003, Su et al. 2015).

While any additional emission source of $PM_{2.5}$ 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 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

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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 highest levels in densely populated and lowest in sparsely populated areas. In the future, in the case of strong reduction in anthropogenic sources, this pattern is predicted to shift to one where the highest pollution levels are found in regions of intermediate population density for most regions (Sub-Saharan Africa, Latin America & Caribbean, and Eastern Europe-Russia-Central Asia), resembling more 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 & Southeast 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 $PM_{2.5}$, 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 hypothesise that, if a guidance level for monthly means were to be established, it would lie somewhere between 10 (annual) and 25 µg / m^3 (daily WHO air-quality guidance). These levels of $PM_{2.5}$ 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 $PM_{2.5}$ levels that are reported and compared to WHO or other air-quality guidelines usually include some water content, as opposed to the

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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 Southeast 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 where 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 measure aimed at bringing down wildfire emissions to avoid adverse health effects.

LPJ-GUESS-SIMFIRE only simulates 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 Southeast Asia (see Fig. S1, Table S2), mainly in Indonesia (Field et al. 2009), where they are the dominant pollution source and

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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 realisations 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 of 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 savanna to cropland (Andela and van der Werf 2014).

Apart from the issue of dry vs. wet aerosols and the omission of some difficult to model components, 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 $PM_{2.5}$ 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 study are 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

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during specified time windows, even though wildfire impacts on air quality can have large interannual (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 is also 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 at 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 time scale. Wildfire episodes can elevate $PM_{2.5}$ 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-hour $PM_{2.5}$ limit of 25 µg/m^3 from the WHO air quality guidelines (WHO 2006) is exceeded as a result of wildfire emissions.

5 Summary and conclusions

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- Globally, wildfire emissions are unlikely to thwart aggressive measures to reduce anthropogenic pollutant emissions enough to stay under the ambitious 10 µg / 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 driver for the expected changes in wildfire emissions in Sub-Saharan Africa. For a scenario of high population growth and slow urbanisation, anthropogenic sources could surpass air pollutant emissions from wildfires in most populated areas. Exposure of humans to $PM_{2.5}$ 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 urbanisation and low population growth.

Acknowledgements

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Author contributions: WK conceived of the study, carried out the analysis and wrote the first draft of the manuscript. JFL performed the CAM-Chem simulations. All authors contributed to discussions and writing.

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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, Env. Res. Lett., 7, 044008, doi: 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, 2011.

Amann, M., Bertok, I., Borken-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, Environmental Modelling & Software, 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., 450-451, 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, Nature Climate 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, D. E., Prentice, I. C., and Pereira, J. M. C.: Causal relationships vs. emergent patterns in the global controls of fire frequency, Biogeosci., 11, 5087–5101, 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, Atm. 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 versus realities in a changing world, Phil. Trans. R. Soc. B, 371, 20150345, 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, Frontiers in Ecology and the Environment, 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 Biology, 21, 1236-1248, 2015.

EEA: Air quality in Europe - 2014 report, European Environmental Agency Report

No 5/2014, 80 pp., doi: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, Nature 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, Clim. 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, doi: 10.1071/wf08187, 2009. 483-507, 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-Biogeo, 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, Clim. 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 (PM2. 5) exposure during wildfires on cardiovascular health outcomes, Journal of the American Heart Association, 4, e001653, doi: 10.1161/JAHA.114.001653, 2015.

Hurtt, G. C., Chini, L. P., Frolking, 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, Environmental science & technology, 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 Environmental Change, 2015. 2015.

Kaiser, J. W., Heil, A., Andreae, M. O., Benedetti, A., Chubanova, N., Jones, L., Mocrette, 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, Biogeosci., 9, 527-554, 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, Journal of Geophysical Research: Atmospheres, 107, 2002.

Kelley, D. I. and Harrison, S. P.: Enhanced Australian carbon sink despite increased wildfire during the 21st century, Environ. Res. Lett., 9, 104015, doi: 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 dioxid: 2000-2011 emissions, Environ. Res. Lett., 8, 014003, 2013.

Kloster, S., Mahowald, N. M., Randerson, J. T., Thornton, P. E., Hoffman, F. M., Levis, S., Lawrence, P. J., Feddema, J. J., Oleson, K. W., and Lawrence, D. M.: Fire dynamics during the 20th century simulated by the Community Land Model, Biogeosci., 7, 1877-1902, 2010.

Knorr, W., Lehsten, V., and Arneth, A.: Determinants and predictability of global wildfire emissions, Atm. Chem. Phys., 12, 6845–6861, 2012.

Knorr, W., Kaminski, T., Arneth, A., and Weber, U.: Impact of human population density on fire frequency at the global scale, Biogeosci., 11, 1085-1102, 2014.

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, 2016a.

Knorr, W., Jiang, L., and Arneth, A.: Climate, CO_2, and demographic impacts on global wildfire emissions, Biogeosci., 13, 267-282, 2016b.

Knorr, W., Arneth, A., and Jiang, L.: Demographic controls of future global fire risk, Nature Climate Change, doi: 10.1038/NCLIMATE2999, 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, doi: 10.1371/journal.pone.0005102, 2009.

Lamarque, J.-F., Emmons, L., Hess, P., Kinnison, D. E., Tilmes, S., Vitt, F., Heald, C., Holland, E. A., Lauritzen, P., and Neu, J.: CAM-chem: Description and evaluation of interactive atmospheric chemistry in the Community Earth System Model, Geoscientific Model Development, 5, 369, 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, 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,

Wolfgang Knorr 3/5/2017 10:38

Deleted: Lamarque, J.-F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., and Owen, B.: Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, Atmos Chem Phys, 10, 7017-7039, 2010.

054010, doi: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, Nature 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., Siegert, 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 Biology, 2016. 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, 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, Environmental Research Letters, 11, 124013, 2016.

Shindell, D. T., J.-F. Lamarque, M. Schulz, M. Flanner, C. Jiao, M. Chin, P. J. Young, Y. Lee, G. Milly, G. Faluvegi, Y. Balkanski, W. J. Collins, A. J. Conley, S. Dalsoren, R. Easter, S. J. Ghan, L. Horowitz, X. Liu, G. Myhre, T. Nagashima, V.

Naik, L. Rotstayn, S. Rumbold, R. Skeie, K. Sudo, S. Szopa, T. Takemura, J.-H. Yoon, Radiative forcing in the ACCMIP historical and future climate simulations, Atmos. Chem. Phys., 13, 2939-2974, doi:10.5194/acp-13-2939-2013, 2013.

Silva, R. A., J. J. West, Y. Zhang, S. C. Anenberg, J.-F. Lamarque, D. T. Shindell, W. J. Collins, S. B. Dalsøren, G. Faluvegi, L. W. Horowitz, T. Nagashima, V. Naik, S. Rumbold, R. Skeie, K. Sudo, T. Takemura, D. Bergmann, P. Cameron-Smith, I. Cionni, R. M. Doherty, V. Eyring, B. Joesse, I. A. MacKenzie, D. Plummer, M. Righi, D. S. Stevenson, S. Strode, S. Szopa, G. Zeng, Global premature mortality due to anthropogenic outdoor air pollution and the contribution of past climate change. Environ. Res. Lett., 8, doi:10.1088/1748-9326/8/3/034005, 2013.

Silva, R. A., J. J. West, J.-F. Lamarque, D. T. Shindell, W. J. Collins, S. Dalsoren, G. Faluvegi, G. Folberth, L. W. Horowitz, T. Nagashima, V. Naik, S. T. Rumbold, K. Sudo, T. Takemura, D. Bergmann, P. Cameron-Smith, I. Cionni, R. M. Doherty, V. Eyring, B. Josse, I. A. MacKenzie, D. Plummer, M. Righi, D. S. Stevenson, S. Strode, S. Szopa, and G. Zeng, 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, doi:10.5194/acp-16-9847-2016, 2016.

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, http://www.fao.org/docrep/ARTICLE/WFC/XII/0278-B1.HTM, 2003.

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, 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, Journal of Geophysical Research: Atmospheres, 114, 2009.

Stohl, A., Aamaas, B., Amann, M., Baker, L., Bellouin, N., Berntsen, T., Boucher, O., Cherian, R., Collins, W., and Daskalakis, N.: Evaluating the climate and air quality impacts of short-lived pollutants, Atmos Chem Phys, 15, 10529-10566, 2015.

Su, L., He Y. and Chen, S.: Temporal and spatial characteristics and risk analysis of forest fires in China from 1950 to 2010.,Scientia Silvae Sinicae 51, 88-96, 2015 (in Chinese with English abstract and figure captions).

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, Ecological Applications, 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, Bull. Am. Meteorol. Soc., 93, 485-498, 2012.

Tilmes, S. , J.-F. Lamarque, L. K. Emmons, D. E. Kinnison, D. Marsh, R. R. Garcia, A. K. Smith, R. R. Neely, A. Conley, F. Vitt, M. ValMartin, H. Tanimoto, I. Simpson, D. R. Blake and N. Blake. Representation of the Community Earth System Model (CESM1) CAM4-chem within the Chemistry-Climate Model Initiative (CCMI). Geosci. Model Dev., 9, 1853-1890, doi:10.5194/gmd-9-1853-2016, 2016.

Tsyro, S.: To what extent can aerosol water explain the discrepancy between model calculated and gravimetric PM 10 and PM 2.5?, Atmos Chem Phys, 5, 515-532, 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, 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, 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, Clim. Change, 109, 5-31, 2011.

Veira, A., Kloster, S., Wilkenskjeld, S., and Remy, S.: Fire emission heights in the climate system–Part 1: Global plume height patterns simulated by ECHAM6-HAM2, Atmos Chem Phys, 15, 7155-7171, 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., S. J. Smith, R.l A. Silva, V. Naik, Y. Zhang, Z. Adelman, M. M. Fry, S. Anenberg, L. W. Horowitz, J.-F. Lamarque, Co-benefits of Global Greenhouse Gas Mitigation for Future Air Quality and Human Health, Nature Climate Change, 3, 885-889, doi: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, 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-21st 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, 2015.