Reply to referee reports on Climate and demographic impacts on wildfire air pollution hazards during the 21st century" by Wolfgang Knorr et al.

Anonymous referee #1:

COMMENT 1

"The manuscript analyses simulations presented in Knorr et al. 2006abc with a focus on PM2.5 emissions during the 21st century in relation to WHO air quality guidelines. The topic is interesting and suitable for publications in ACP. As a reader I do have however problems to figure out what I learned from this manuscript especially regarding the distinction in climate and demographic impacts. The manuscript is very lengthy and not well structured. As the simulations have been analysed in great detail in previous publications, I suggest to significantly shorten some of the analysis and parts of the discussion and refer more to the previous publications."

REPLY 1

The guiding question for this manuscript, as opposed to the previous publications the referee alludes to, was whether different future wildfire scenarios would have a discernible impact globally on our ability to meet WHO air quality guidelines. For that, we largely used a methodology taken from Knorr et al. 2016c. Following suggestions by Referee #2, this simplified methodology for computing pollutant concentrations has been abandoned and a set of four gobal chemistry-climate model simulations with fixed meteorology have been added. Because of computational cost, these simulations only concern one time window (2090) and they cannot be used to distinguish between the effects of urbanisation vs. population growth.

As a result, the revised manuscript is now much more focussed on the initial question. The title has been shortened in order to reflect that, removing explicit reference to climate vs. demographic effects.

The detailed presentation of future changes in emissions (current Sub-Section 3.2) has been removed entirely, including associated discussions, and the figures have been relegated to Supplementary Information. Any results other than for PM2.5 have also been removed fro the main text. Also removed has been the detailed analysis of exposure levels and the impact of demographic changes. Future changes in wildfire emissions are now only presented in the context of a comparision with concurrent anthropogenic-emissions scenarios. Instead, the focus is now much more on regions where differences between wildfire emission scenarios might have a discernable influence on future pollution levels and our ability to meet health related PM2.5 concentration targets.

Figures 2, 4, 5, 6 have been moved to newly added supplementary information (replacing the appendix).

Table 1 has been cut to show on only results for PM2.5.
Tables 2 and 3 and Figure 9 have been removed and replaced by a new Table 2 and Figure 6, showing exposed population based on the newly added simulations with the chemistry-climate model.

COMMENT 2

"In general throughout the manuscript the distinction between climate and demographic impacts on wildfire air pollution hazards during the 21st century is hard to follow (see various comments below). The climate and demographic impacts on fire activity during the 21st century have been discussed in detail in earlier publications (Knorr et al.,2016ab) based on the same simulations but focusing on fire carbon emissions and burned area. Even though this paper focuses on PM2.5 emissions I'd assume that the major conclusions would be the same and suggest to focus this paper solely on the changes in wildfire air pollution hazards during the 21st century in relationship to changes in anthropogenic emissions."

REPLY 2

See Reply 1.

Following a similar comment from Review #2, we have added a paragraph at the beginning of Sub-Section 3.3 (now 3.2), which summarizes the results of Knorr et al. (2016b).

COMMENT 3

"Abstract: Line 32: The importance of wildfire emissions are in the abstract mainly discussed relative to the changes in anthropogenic emissions, but not in the light of changing fire emissions. E.g. wildfire emissions decline drastically in the future for Sub-Saharan Africa according to your simulations. This should be discussed more carefully in the abstract.

REPLY 3

Point taken, thank you. The revised abstract now ends as follows:

"Under a scenario of high population growth and slow urbanisation, wildfire emissions strongly decline in large parts of Sub-Saharan Africa, making anthropogenic emissions the dominant sources of PM2.5 unless they are reduced drastically. However, if anthropogenic emissions are strongly reduced, changes in PM2.5 pollution stemming from wildfires may in some regions tip the balance between reaching or failing the World Health Organization air quality targets, including most African savannas and semi-arid woodlands, southern China, parts of Southeast Asia, and the semi-arid regions south of the central Amazon."

Indeed, wildfire emissions in Sub-Saharan Africa won't decline much under different demographic assumptions, e.g. when there is rapid urbanisation and slow overall population growth, leading to a reduction in rural population.

COMMENT 4

"Line 37: will this not suffice because wildfire emissions are high anyway, because they become enhanced in the future, or they are not strongly enough reduced? Please, be more precise."

REPLY 4

Point taken. This sentence has been revised in the light of the newly added chemistry-climate model simulations.

See Reply 3.

COMMENT 5

"Method: LPJ-GUESS-SPITFIRE results as published in Knorr et al., 2016ab are used to scale GFED4s observation based PM2.5 emissions into the future. Two scalars are introduced a population and a climate, vegetation scalar. The simulations introduced in Knorr et al., 2016b includes a simulation in which only the climate/vegetation effect is accounted for. Couldn't this simulation be used to distinguish between the population and climate impact."

REPLY 5

We assume the reviewer refers to LPJ-GUESS-SIMFIRE, not SPITFIRE. In contrast to Knorr et al. (2016b), which uses factorial analysis to differentiate between different driving factors, this manuscript focusses on the question of what difference different wildfire emission scenarios would make for meeting air quality targets. In the revised manuscript, this is done by comparing two scenarios for 2090, emissions of which were fed to a chemisty-climate model: SSP5 demographics coupled with RCP8.5 climate change (slow population growth with rapid urbanisation in developing countries, but high population growth in rich countries, with globally high greenhouse gase emissions), vs. SSP3/RCP4.5 (slow urbanisation and rapid population growth in developing countries, low population growth in rich countries, combined with moderate future greenhouse gas emissions), both under a scenario of maximum feasible reductions (MFR) for anthropogenic emissions.

By comparing these two scenarios, we can extract the impact of differences in wildfire emissions scenarios.

COMMENT 6

"The population scalar is defined for each grid box, while the climate, vegetation scalar is averaged per country/region. How will this impact the results? Also Knorr et al., 2016c did not use a climate and population scalar. Does this lead to different results for Europe?"

REPLY 6

In the revised manuscript, results differ from those for Europe presented in Knorr et al. 2016c not only because of the use a population scalar at grid cell resolution, but also by the use of chemistry-climate model simulations.

The introduction of a separate vegetation/climate and population scalar (Equ. 1 to 3) is an improvement on the methodology introduced by Knorr et al. (2016a) and is not related to any factorial analysis. In Knorr et al. (2016a), the emissions of a given country are simply assumed to scale up or downwards by the same factor over the entire surface area, inrelated to whether an area is urban or rural. A statement was added at the end towards the end of Sub-Section 2.3 (before the introduction of the chemistry-climate model simulations).

COMMENT 7

"3.2. Simulated changes in emissions In discussing the trend in simulated changes in PM2.5 emissions it is for various regions differentiated whether the trend is dominated by climate or population changes (e.g. line 28-21, 326, 339, 317,353, 443,472,674). Given the results discussed in the manuscript I do not see how the overall simulated trend can be disentangled in climate and population driven. While the method section introduces a population and vegetation/climate scalar, this is not further used or shown in the result section."

The population scalar was not introduced to distintinguish between climate and population effects, see Reply 6

The reviewer is right in suggestion that the results presented do not constitute a factorial setup as done by Knorr et al. (2016b). The results of this study are now summarized in a short paragraph, to make this clearer (see Reply 2).

In the revised manuscript, we focus on the difference between two wildfire emission scenarios, and the impact that has on pollution levels. We hope that this clarifies the confusion. See also Reply 5.

COMMENT 8

"Line 305: isn't it sufficient to discuss the changes in scaled GFEDv4 emissions? The changes from the simulations with LPJ-GUESS-SPITFIRE have been discussed in previous publications (Knorr et al., 2016ab). I suggest to shorten this section and refer more to your analysis made in previous publications."

REPLY 8

The material presented in this sub-section (3.2) has been moved to the supplementary material as reference material. This indeed broadly repeats results of previous publications, but gives more detail and is tied to the spatial analysis method used here.

We have added a short statement at the start of 3.3 (now 3.2) referring to the supplementary material and to Knorr et al. 2016b. This includes what is currently discussed in Lines 363 to 369. (See also Reply 2).

COMMENT 9

"Line 330: Similar to what?
Line363: The changes in scaled GFED emissions should be discussed in a new sec- tion.
Line370: country/region
The results in many cases are discussed along with changes in population density of the different SSP scenarios. Here a figure illustrating the changes in the single SSP scenarios considered in e.g. the Appendix would be helpful for the reader. Figure A3 partly shows this, but is not referenced in section 3.2."

REPLY 9

These parts of the manuscript has been removed following both reviewer's suggestion of significantly shortening the manuscript, see also previous Reply 8.

References to Figure A3 (now Figure S3 of the Supplementary Information) have been added where appropriate.

COMMENT 10

"3.3. Predicted changes in emissions by population density I do have problems to follow the arguments in this section. Line397:. Why is it important that the decline is absent in RCP85/SSP5 and why does an increase in population density within a given category lead to more fire suppression? What is the relation to Figure 1 and A2?"

A similar analysis is shown in Knorr et al. 2016a, but for burned area, and using grass/tree fraction as an additional dimensions. The arguments presented in the part referred to by the reviewer are indeed hard to follow. This text has been removed as part of a major revision of Sub-Section 3.2 (now 3.2).

COMMENT 11

"Line 399: why does woody encroachment get important here. It is not discussed anywhere else."

REPLY 11

Woody encroachment is actually first introduced in Line 62 of the submtted manuscript. In the revised version, it is also taken up again at the beginning of Sub-Section 3.2, where the results of Knorr et al. (2016b) are summarized (see also Reply 2).

COMMENT 12.

"Line 409: From the figure I'd think that High-Income Europe shows the same pattern."

REPLY 12

This statement refers to Fig. 7 (now Fig. 3) and is valid for SSP3/RCP4.5. Here, middle and low-income countries have a slow urbanisation rate, and emissions in the most densely populated category indeed increase for all except the high-income regions (Austriala & New Zealand, North America, High-Income Europe).

This has been clarified.

COMMENT 13

"Changes in population impact the changes in emissions by population density because: (1) wildfire activity changes with changing population density and (2) regional changes in population distribution. On top changes in climate will change the regional distribution of fire prone areas. Is there a way from your simulations to disentangle these factors more quantitatively than discussing Figure 7?"

REPLY 13

We believe that Figure 7, in particular, shows imporant shifts in pollution hazard, for example for Sub-Saharan Africa, South & Southeast Asia Latin America and Caribbean away from sparsely towards densely populated regions. We do not know of a straightforward approach for disentangling all those factors, but believe nevertheless that this is important information that means that a broad decline in fire acitivity does not necessarily mean a similar decline in exposure to humans.

We have added text to clarify what is seen in those figures showing emissions or concentrations (newly added Fig. 6) by range of population density (third paragraph of new Sub-Section 3.2).

COMMENT 14

"Line444: Many area in Africa? Line446: I can not identify an additional zone further south in Figure 9. Line448: how do you distinguish between climate and demographic control. Line452: It is impossible to identify any change in Portugal from Figure9. Figure 9: To include a category exceeded under current conditions would be helpful."

REPLY 14

In the light of the results of the chemistry-climate model simulations, the analyses of emissions above a certain threshold have (Figures 9, A4 and A5) have been removed and replaced by an analysis of regions or populations where simulated PM2.5 concentrations exceed 10µg/m3 (new Table 2, Figure 9).

COMMENT 15

"The analysis discussed in the paragraph line 456 and following is the most relevant in the manuscript. I'd suggest to include these results in the abstract."

REPLY 15

This part has been thoroughly revised given the results from the chemistry-clmate model simulations.

COMMENT 16

"Line 512: The discussion of simulation results for Western US seems a bit out of context. I suggest to remove it."

REPLY 16

Done as suggested.

COMMENT 17

"Line 527: "broadly reconfirms" this is misleading. All studies (Knorr 2016abc) and this one are based on the same simulations."

The word "re-confirm" is indeed not appropriate in this context. This part of the text has been removed.

COMMENT 18

"Line 534: wildfire risk to humans – how do you define this? Line 537: climate and vegetation changes – you did not discuss vegetation changes Line 539: the approaches – which approaches? Line 552: Both studies? Which studies? Does Giglio et al. use country information? Also as for as I understand does this study only scale the climate/vegetation part by country/region. The population scaling is done on a gridbox level. Line559: Do not understand why this explains that deforestation and peat fires are excluded."

REPLY 18

"wildfire risk to humans" , "climate and vegetation changes": the complete text encompassing these lines has been removed during the revision.

"the approaches", "deforestatino and peat fires": the paragraph Lines 539-556, which includess these two points, has been removed.

We have, however, added reference to Marlier et al. (2015), a study on air pollution due to peat fires in Indonesia, at the end of the last paragraph but one of Sub-Section 3.1.

COMMENT 19

"Line 579: in accordance with the results of Andela and van der Werf (201X). The increase that was discussed by Andela and van der Werf is caused by the analysis of a timeperiod with an incomplete El Nino cycle it should be not interpreted as a trend."

REPLY 19

Agreed. This has sentence in Line 576-579 has been deleted from the discussion.

COMMENT 20

"Line 580:"are broadly representative" you compared with one study in Africa and one in the western US. This is not enough to come to any conclusion on the representativeness of the model as a whole. Given that the results of the model have been used in previous studies I'd expect that the evaluation of the model has been discussed in more detail in these studies."

REPLY 20

Agreed. This sentence in Line 579-582 has been removed.

COMMENT 21

"Line 597: “This is opposite to what we find ..” Is this opposite for all regions or only sub-Saharan Africa. Please be more precise."

REPLY 21

This part - the entire paragraph Lines 583-601, has been removed, making space for the discussion of the results of the chemistry-climate model simulations.

COMMENT 22

"Line 652: “ and climate change will lead to new areas” the impact of climate will be the same for MFR and CLE."

REPLY 22

This comment seems to refer to Line 622. The sentence continues with "wildfire emissions", which are affected by different climate scenarios.

COMMENT 23

"Line 646: The discussion of the emission inventories by Kaiser and van der Werf seems out of context."

REPLY 23

This part has been removed as suggested.

COMMENT 24

Line 655: changes?

REPLY 24

It should have been "changes in", this has been corrected.

COMMENT 25

"Minor comments:
Line 51: “. . . due to climate change efforts to reduce anthropogenic emissions . . ..
“I do not understand the connection.
Line 53: Reference Flanning et al., 2012 is missing.
Line 56: please specify the regions these studies are for.
Line 132: climate change → emission
Line 171: the reference to figure A1 is not clear to me. Figure A1 would be helpful in the result section.

Line 265: Given that the manuscript is already quite long. I'd suggest to leave out the NOx and CO analysis. As the authors state, anthropogenic sources are dominant.
Line 287: proper ?
Line 296: Threshold of 1 inh./km2 to distinguish between anthropogenic and wildfire dominance. I can not identify this in Figure 3. Is this for all regions?
Line 305: I do not get how this differs. When the trend of LPJ-GUESS-SPITFIRE is used to scale GFEDv4. The relative temporal changes should be the same.
Line 316: Demographic trends are by far the dominant driver, while the differences in climate scenarios are minor. I do not see how you draw this conclusion from the presented results. Your have two simulations with different climate projections, but no simulation without the climate or population effect. That the differences between RCP45 and RCP85 are only minor, does not imply that the climate impact is not important.
Line 326: .. fire activity driven by population trends. Similar to comment line 316.
Line 334: .. climate is the dominant driver. Similar to comment line 316.
Line 363: The comparison of LPJ-GUESS-SIMFIRE and GFEDv4s does not fit so well in the section 'emission changes' as it discusses only the present day emissions. Maybe this could go into the method section?
Line 442: For which timeperiod?
Line 444: .. but do not exceed them in 2090 ?
Line 464: scenario → threshold
Line 481: not sure I understand what you mean. Area that are exceeding verus areas that will fall below the threshold.
Line 515: Doer and Santin does not discuss the future.
5 Summary and Conclusions I'd suggest the remove the first paragraph on future fire emission for Western US. This is not the focus of the study.
Typos: Line 340: of? Line 376: Africa, South Africa Line 377: shows Line 960: and SSP5"

REPLY 25

Line 51: wildfires will become more important because (a) the increase and (b) other pollutant sources decrease; but it is not clear that there is much awarness of the fact that if anthropogenic emissions are drastically reduced, there might be a remaining problem with pollution from wildfires. We have therefore removed reference to anthropogenic emissions and the EEA publication.
Line 53: Reference Flanning et al., 2009 has been added and reference year (2012) has been corrected.
Line 56: Canada and southern Europe, this information has been added
Line 132: high emissions, but also high degree of climate change
Line 171: you can check areas with more than 100 inhabitants per km2 in Figure A1 (now S1).
Line 265: results for NOx and CO have been moved to the Supplementary Information
Line 287: changed to "continental South-East Asia"

Line 296: The threshold is simply the cross-over point where the dominant source (wildfires or anthropogenic) changes. This has been clarified (see last sentence of Sub-Section 3.1).
Lines 305, 316, 326, 334: this part has been removed as part of Sub-Section 3.2.
Line 363: This paragraph has been moved to the beginning of the same sub-section as an introduction, following a paragraph summarizing the results of Knorr et al. (2016b).
Lines 442, 444, 481: these belong to previous Sub-Section 3.4, which has been replaced by a new presentation of the results of the chemistry-climate model simulations.
Line 515, Summary and Conclusions: this refers to the situation in the western US, which has been removed (see Reply 16).
Typos: of -> on, correct as is, correct is, corrected.

Anonymous referee #2:

COMMENT 1

"I cannot recommend the paper for publication as the paper's method for calculating mean PM2.5 concentrations at the surface is simplistic. The authors neglect horizontal transport between 0.5 x 0.5 gridcells and compute an annual budget based on annual mean emissions and pollutant lifetime. But smoke can be transported many hundreds of kilometers downwind of source fires. See for example Lee et al. (2005), Singh and Kaskaoutis (2014), and Marlier et al. (2015). The approach in this paper likely overestimates PM2.5 in source regions and underestimates PM2.5 in regions downwind."

REPLY 1

Following this comment, we have now performed a limited (due to cost) number of global chemistry-climate model simulations on a one by one degree grid and with present-day meteorology. Using the definition of an (effective) ventilation rate l as in C=E/l (C: concentrations, E emissions) we calculate a global l for PM2.5 of 307m/day. We can also derive a global l for anthropogenic (316 m/day) and wildfire emissions (760 m/day) separately using the differences in emissions and concentrations between the MFR/SSP5/RCP8.5 and the MFR/SSP3/RCP4.5 scenarios. Doing the same analysis for boreal Russia (60N and up), we find l=63m/day for anthropogenic PM2.5 and l=683m/day for wildfires. In the present manuscript, by contrast, we assume l=1000m/(1/50year)=136m/day, which is turns out to be much more suitable for anthropogenic emissions, but not for wildfires.

We have therefore removed all analysis that refers directly or indirectly to the simplified assumption about atmospheric transport (including Tables 2, 3 and Figure 9), and have added new methods, results and discussion for the model simulations of PM2.5 concentrations at surface level (incl. new Table 2 and Figures 5 and 6).

Because of the limited number of simulations, we have also removed the detailed analysis of the impact of urbanisation vs. population increase in pollution levels, which could not be performed using simulated PM2.5 levels.

A reference to Lee et al. (2005) has been added at the beginning of the introduction section, and a reference to Marlier et al. (2015) to the end of the last paragraph but one of Sub-Section 3.1.

COMMENT 2

"Other criticisms. 1. The authors need to better identify the new results in this work. For example, it wasn't clear whether the finding that population density could affect future wildfires occurrence had already been presented in Knorr et al. (2016). A brief 1-2 paragraph summary of the Knorr et al. (2016) results would be helpful to clear up this confusion. Detailed reasons for the modeled response of wildfire to climate change were absent in the current paper, and the summary could succinctly describe these drivers as determined by Knorr et al. (2016). The summary could also describe what triggers fires in LJM-GUESS and reassure the reader that present-day fire occurrence and area burned have been validated against observations."

REPLY 2

Because of the changes described in Reply 2, the focus of the manuscript has shifted away from a detailed analysis of the drivers of changes in air pollution, with a new focus on regions where wildfire emissions might severely impact atmospheric pollution levels. The sub-section "Predicted changes in emissions" (3.2, formerly 3.3) now only analyses regional changes in the distribution of emission rates against populaton density, something that was not presented earlier.

We have added at the beginning of this sub-section a short paragraph summarizing the results of Knorr et al. (2016), followed by a paragraph comparing simulated emissions against GFED4.1, taking from former sub-section 3.2, which has been deleted.

COMMENT 3

"The authors should focus just on trends in wildfire smoke, not in anthropogenic pollution. The atmospheric community has already extensively examined projected trends in anthropogenic pollution (e.g., Fiore et al., 2012). As is, it is difficult for the reader to determine what accounts for the PM2.5 trends in Figures 4 and 5."

REPLY 3

These figures have been moved to the Supplementary Information, see Reply 1.

However, we have retained the comparison with anthropogenic emissions, as suggested by Referee #1.

We have added a reference to the PM2.5 simulations presented by Fiore et al. (2012)
at the beginning of the discussion section, and a reference to the discussion of the role of wildfires in climate-atmospheric chemistry feedbacks, also by Fiore et al. (2012).

COMMENT 4

"The paper describes three types of fires: wildfire, deforestation fires, and peat fires. It looks like agricultural fires are lumped in with wildfires. Is that right, and if yes, what does that mean for projected area burned? Some studies put agricultural fires at 10% of total fire occurrence (e.g., Korontzi et al., 2006), with areas such as China and eastern Europe exhibiting much larger occurrences. See also Singh and Kaskaoutis(2014) regarding agricultural fires in India and Figure 12 in van der Werf et al. (2010), which puts wildfire emissions from agricultural burning at 25-30% in Europe and central Asia, including China.

It's also not clear how deforestation and peat fires are distinguished from wildfires."

REPLY 4

Following van der Werf et al. 2010, deforestation fires are considred fires associated with deforestation activities, peat fires those that occur on forest or non-forested peatlands , while agricultural waste burning is not included with wildfires. Agricultural burning is indeed assumed to be part of the anthropogenic emissions.

We have added a paragraph at the beginning of Sub-Section 2.3 to clarify this.

We have also added a reference (Su et al. 2015) that documents that in southern China, there is indeed a substantial amount of burned area attributed to forest fires. Note that even though the publication is in Chinese, figure captions and abstract are available in English.

COMMENT 5

"It's not clear that the authors have validated the PM2.5 results against observations. Given the simple method of calculating PM2.5 concentrations, readers are curious how well this method works. Also does the PM2.5 in their calculations include both black carbon and organic carbon?"

REPLY 5

Black carbon and organic carbon are included in the newly added chemistry-climate model simulations, and are therefore part of PM2.5. These are described in a newly added paragraph of Sub-Section 2.2.

A reference that describes this model has been added (Lamarque et al. 2010), where simulations have been evaluated against observations.

COMMENT 6

"The paper is long, about double what is needed. The authors should decide on key points regarding wildfire PM2.5 and delete the rest."

We have removed sub-section 3.2, the analysis of emission rate thresholds, and the discussion of the relative impact of urbanisation vs. population increase, but added chemistry-climate simulations. These, however, are used for a limited purpose, i.e. identifying regions where differences between wildfire emissions scenarios could make difference for meeting the WHO concentration threshold. See Reply 2.

COMMENT 7

"The paper focuses on annual mean PM2.5, when fire is episodic and strongly seasonal. Emerging evidence suggests that smoke episodes have large impacts on human health, even if the annual mean PM2.5 is lower than the EPA threshold. Using annual mean PM2.5 minimizes the importance of such episodes as well as the seasonality. See for example, Haikerwal et al. (2015). It would be good if the paper could discuss PM2.5 trends during wildfire seasons, which differ around the world."

We have added an analysis of PM2.5 concentration and human exposure during the month where PM2.5 is highest (Table 2, Fig. 6). Seasonality in concentrations can also occur due to mixing of anthropogenic emissions, which are assumed to have no seasonal cycle. We find that exposure to peak-month pollution levels is influenced much more by the wildfire emission scenario than mean annual concentrations. The results are included in the completely revised Sub-Section 3.3.

A reference to the health impacts and Haikerwal et al. (2015) has been added at the end of the Discussion section, where it was already suggested that future studies should examine short-term fluctuations of PM2.5 from wildfire smoke.

COMMENT 8

"Other relevant papers that examine wildfire PM2.5 in the future atmosphere include Spracklen et al. (2009), Pechony et al. (2010), and Yue et al. (2013)."

REPLY 8

We thank the referee for his thorough and very helpful reference to existing publications. We did not include references to Spracklen et al. (2009) and Yue et al. (2013) because we have dropped discussion of Western U.S. changes in wildfire emissions and air pollution following a suggestion of Ref. #1 and because we felt we needed to shorten the manuscript. Pechony and Shindell (PNAS, 2010) only discusses changes in fire activity in broad terms, and this reference is therefore not included here, either.

Title:

Wildfire air pollution hazard during the 21st century

Authors:

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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. Various studies have pointed out that climate change, increasing atmospheric CO_2, as well as demographic dynamics can lead to substantially increased wildfire activity, but also that under certain conditions, fire activity may continue to decline throughout most of the 21st century. The present study re-examines these results from the perspective of air pollution risk, focussing on emissions of airborne particulate matter (PM2.5). We combine an existing ensemble of simulations using a coupled fire-dynamic vegetation model with current observation-based estimates of wildfire emissions and simulations with a chemistry–climate model to predict future emissions and surface-level concentrations of air pollutants and exposures of population. Currently, wildfire PM2.5 emissions exceed

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those from anthropogenic sources in large parts of the world, while emissions from deforestation or peat fires constitute minor sources globally. Under a scenario of high population growth and slow urbanisation, projected future wildfire emissions strongly decline in large parts of Sub-Saharan Africa, making anthropogenic emissions the dominant sources of PM2.5, unless they are reduced drastically. However, if anthropogenic emissions are strongly reduced, changes in PM2.5 pollution stemming from wildfires may tip the balance between reaching or failing the World Health Organization's air quality targets in many regions, including most African savannahs and semi-arid woodlands, southern China, parts of Southeast Asia, and the semi-arid regions south of the central Amazon.

1 Introduction

Wildfires are a major natural hazard (Bowman et al. 2009) and an important source of air pollutants (Langmann 2009), which can impact levels of air pollution thousands of kilometres downwind (Lee et al. 2005). Wildfires also play in important role in several atmospheric chemistry–climate feedback mechanisms (Fiore et al. 2012). Emissions of fine aerosol particles, i.e. particulate matter up to a diameter of 2.5 micrometers (PM2.5), are of a particular health concern, with no known safe levels of PM2.5 concentration in air, as noted by the World Health Organization (WHO 2006). While, at present, globally most PM2.5 emissions come from human activities, wildfires can be an important source in large, more remote areas (Granier et al. 2011, van der Werf et al. 2010). 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).

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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 predicted fire severity indices from climate argue for large increases in burned area as a result of climate warming (see for example Flannigan et al. 2005 for Canada, and Amatulli et al. 2013 for southern Europe). 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 also responds to climate change, as well as 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. 2016b). Indeed, simulations with coupled fire-vegetation or statistical climate-envelope models generally show less increase in fire activity until 2100 when accounting not only for climate, but also for these vegetation factors (Krwachuk et al. 2009, Kloster et al. 2010, Knorr et al. 2016c).

Another factor that has so far received less attention are changes in human population growth and distribution. Contrary to common perception, higher population density tends to be associated with lower wildfire risks measured by burned area (Archibald et al. 2009, 2010, Lehsten et al. 2010, Knorr et al. 2014, Bistinas et al. 2014), even though a larger population density 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 is less manifested as enhancing

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burned area by providing ignitions, 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 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), or even a decline in burned area (Knorr et al. 2016c) or emissions (Knorr et al. 2016b) for moderate levels of climate change combined with slow urbanisation and high population growth. There is also observational evidence for 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 have been related to the expansion of cropland, that is itself a result of increasing population density (Andela and van der Werf 2014).

It is therefore important to consider not only climate and CO_2 scenarios, but also scenarios of demographic changes. Building on a similar study for Europe (Knorr et al. 2016a), we compute future levels PM2.5 pollution from wildfires and anthropogenic sources (including agricultural burning) using observation-based wildfire emissions, vegetation-fire model simulations to project relative changes in emissions, and simulations with a chemistry-climate model to compute surface-level pollutant concentrations. The results are meant to be indicative of the importance of changes in the global wildfire regime for air quality and atmospheric pollutant load, as compared to anthropogenic and other sources. All this, however, needs to be seen against a background of considerable uncertainties surrounding both current trends (Doerr and Santin 2016) and future projections of wildfire emissions (Knorr et al. 2016a).

2 Methods

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2.1 Vegetation-fire model and driving data

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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). A detailed description of the coupling between SIMFIRE and LPJ-GUESS and of methods used to compute wildfire emissions in terms of biomass can be found in Knorr et al. (2016b). LPJ-GUESS is a patch-scale dynamic vegetation model that represents age cohorts 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 (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 50% past or future cropland area (in either the RCP6.0 or 4.5 land use scenarios of Hurtt et al. 2011) were excluded from the calculations (see Knorr et al. 2016b, c for details).

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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 between fires in (1) savannahs and grasslands, (2) tropical, (3) boreal and (4) temperate forests. We assign a grid cell to

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(1) if the dominant PFT (the one with the largest leaf area index at full leaf development) is a grass, to (2) if it is a tropical, to (3) a boreal and to (4) a temperate woody plant (see Knorr et al. 2012 for list of PFTs).

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° x1° 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. 2016b). 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 range of socio-economic, demographic and biophysical factors. We note that not all RCPs are compatible with all SSP assumptions, and those specific combinations were excluded from further analysis. Globally, SSP2 reflects an intermediate case (medium population and economic growth and a central urbanisation case), SSP3 high population growth and slow urbanisation with slow economic development, and SSP5 rapid but fossil-fuel driven economic growth with slow population growth and fast urbanisation. However, there are regional variations in demographic trends under each SSP. In contrast to developing countries and the world as a whole, high-income countries have low population growth for SSP3, but high population growth for SSP5. We did not consider the SSP1 scenario because its sustainability assumptions

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lead to low emissions and the scenario is therefore not compatible with the RCP8.5 climate scenario, nor did we use SSP4, since it is similar to SSP2 in its population projections. The matrix of three SSPs and two RCP scenarios represents a wide range of future climate and socio-economic conditions.

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 groups of countries (following the methodology of Knorr et al. 2016a). 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 (SI). The use of countries accounts for the high degree of policy or cultural impact on fire regime (Bowman et al. 2009). In order to account for demographic effects at the grid-cell scale, we combine a scalar accounting for climate and vegetation effects, f_{cv}, which is uniform in space across each region, with a scalar accounting for demographic effects, f_p, which is applied at each grid cell separately:

$$E(x,t) = f_{cv}(R(x),t) * f_p(p(x,t)) * E_{GFED}(x) \qquad (1)$$

with E the re-scaled emissions, x the geographic location on the 0.5° x0.5° grid used for the analysis, t the year, R the region/country found at location x, E_{GFED} the annual emissions climatology from GFED 4.1s (average for 1997 to 2014). The population effect, f_p , is equal to the population multiplier of SIMFIRE (Knorr et al. 2016b):

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

p' here is the minimum of population density p and 100 inhabitants per km^2, i.e. the function is constant for values of p above 100 inhabitants per km^2 (Fig. S1). We have introduced this cap, which is only used for scaling observation-based inventories by

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LPJ-GUESS-SIMFIRE output, but not by SIMFIRE itself, in order to prevent large relative increases in emissions resulting from the scaling procedure, when population density decreases from their present values above 100 km^{-2}. We thus consider areas with higher population density than 100 per km^2 to be essentially wildfire free. The combined effect of climate and vegetation on emissions is defined as

$$f_{cv}(R,t) = \Sigma_R\, E(x',t) \;/\; [\Sigma_R\, E(x',t_0) * \Sigma_R\, f_p(p(x',t))]. \qquad (3)$$

Here, the sums are over all grid cells x' of the LPJ-GUESS 1-degree equal-area grid that belong to region/country R. We use t_0=2010 as the reference year, and always compute emissions $E(x,t)$ as 21-year averages centred around year t. 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) we excluded from this scaling procedure by setting $f_{cv}(R,t)=f_p(p)=1$. This procedure retains the seasonal cycle of the GFED4.1 emissions by scaling each month by the same factor. The method is an improvement on the one used for Europe by Knorr et al. (2016a), where all grid cells of a country/region were scaled uniformly and the effect of demographic changes are applied only as a regional/country average, with no differentiation between e.g. rural and urban areas. Gridded population data is based on HYDE 3.1 (Klein-Goldewijk et al. 2010), and future population patterns are re-scaled from 2005 population data using per-country population increases and changes in urbanization level, retaining the urban masks of the HYDE data (see Knorr et al. 2016c for details).

The computed seasonal cycle of 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

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chemistry (CAM-Chem, Lamarque et al. 2010). According to Equ. 1, current emissions were equal to the average seasonal cycle of GFED4.1, and 2090 emissions the same but scaled by the average relative increase between the 2010 (2000 to 2010 average) and 2090 (2080 to 2100 average). Anthropogenic emissions are here assumed 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 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 redistributed within the boundary layer.

Because our analysis focuses on the impact of biomass burning and anthropogenic emissions, four simulations are carried out for a period of 25 months each, and a mean annual cycle is computed from using months 2 to 25. While there is 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.

2.3 Analytical Framework

For wildfires, we use the sum of boreal forest fires, temperate forest fires and savannah fires from GFED4.1s. These are compared to peat and deforestation fires, while 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 are defined as fires caused by deforestation activities, and peat fires are those occurring in forested or non-forested peatlands (see van der Werf et al. 2010).

In our analysis, we use four time windows: current, 2030, 2050 and 2090 for the analysis of emissions, and two (current and 2090) for simulated concentrations. For current, we use 2010 population fields and annual anthropogenic emission data, as well as the mean annual emissions of GFED4.1s, which span the period 1997-2014. For the future time windows, we again use population fields and anthropogenic emissions from that year, but average emissions simulated by LPJ-GUESS-SIMFIRE according to Equ. 1 to 3. While LPJ-GUESS-SIMFIRE simulations are carried out on a 1-degree equal-area grid, all spatially explicit analysis is carried out on a global 0.5° x0.5° grid.

To assess the relevance of PM2.5 emission rates, we compare them to those from anthropogenic sources, and also judge simulated surface concentrations by their proximity to the World Health Organization air quality policy target of 10 µg/m^3 on an annual average, keeping in mind that there is no established safe lower limit and that the target was set considering background concentrations of 3–5 µg 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

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al. 2013, Stohl et al., 2015) for the years 2010 (for current conditions), 2030 and 2050. This dataset provides two future 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), roughly equivalent to RCP6.0. MFR corresponds to a policy driven abatement scenario, implementing all currently known technologies at a reasonable cost, with the aim, among others, to lower PM2.5 emissions to levels with limited health impacts (Amann et al. 2011). Following Knorr et al. (2016a), we estimate 2090 CLE emissions assuming constant *per capita* emissions after 2050 but changing population and urbanization according to the SSP3 scenario. 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). As the CLE and MFR scenarios do not account for CO_2 emissions, both are in principal compatible with the CO_2 equivalent greenhouse gas emissions of both RCP4.5 and RCP8.5, even though the non-CO_2 greenhouse gas emissions may differ.

For a regional analysis, we use a global map of nine major world regions to facilitate a global-scale analysis of our results (see Fig. S2). 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 Eastern Europe and Central Asia, which also includes Russia. Countries of the Middle East (Israel, oil-rich states of the Persian Gulf) or East Asia (Japan, South Korea) belonging to the high-income group were excluded, which only account for a very small fraction of wildfire emissions in their respective group.

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3 Results

3.1 Current patterns of wildfire pollutant emissions

The analysis presented in this sub-section concerns exclusively observation-based emission inventories. According to the GFED4.1s and ECLIPSE inventories (Fig. 1), PM2.5 emissions over large parts of the globe are dominated by wildfires, in particular the boreal zone and the semi-arid tropics (see also Supplementary Information, Fig. S4). Even in the humid tropics, such as the Amazon basin or Southeast Asia, wildfires are prevalent and deforestation fires still play a comparatively minor role. Only Indonesia is clearly dominated by deforestation and peat fire emissions. Of the nine world regions, four (Sub-Saharan Africa, Latin America & Caribbean, Eastern Europe-Russia-Central Asia and Australia & New Zealand) have higher wildfire than anthropogenic emissions of PM2.5 on an annual basis (Table 1). There are also large, remote areas where, despite low emission rates, wildfires are the dominant source of emissions because anthropogenic emissions are even lower (parts of the boreal zone, central parts of Australia, much of the western US, northern part of the Amazon).

A breakdown of PM2.5 emission patterns by population density is shown in Fig. 2. It shows current emissions per area averaged over all grid cells of a given region that fall into a certain population-density range. Fig. 2 reveals the expected trend of increasing anthropogenic emissions where more people live. By contrast, for Sub-Saharan Africa, Latin America & Caribbean, Eastern Europe-Russia-Central Asia and South & Southeast Asia, wildfires show peak values with maximum emissions in regions of intermediate (1 –100 km^2) population density. Deforestation fires are of minor importance for PM2.5 emissions, except in sparsely populated areas of Latin America & Caribbean, and in more densely populated areas of South & Southeast

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Asia. Note that within South & Southeast Asia (Fig. S2), wildfires occur mainly in continental South-East Asia, but deforestation fires in Indonesia (Fig. 1a). Indonesia is also the only region where emissions from peat fires are relatively important for air pollution (Marlier et al. 2015).

In High-Income Europe and Developing Middle East & North Africa, wildfires play a minor role in all categories, for North America, wildfires have a reverse tendency with population density compared to anthropogenic emissions, and for Australia & New Zealand and Developing East Asia, wildfire emissions happen at a similar average rate across all population density categories. Wildfires often become the dominant source below a certain value of population density, which is 100 for Sub-Saharan Africa, 10 for Latin America & Caribbean, Australia & New Zealand and Eastern Europe-Russia-Central Asia, and 1 inhabitant per km^2 for North America and Developing East Asia.

3.2 Projected changes in emissions

Simulated changes CO_2 in emissions have previously been analysed by Knorr at al. (2016b), who found a complex pattern of drivers of future wildfire emissions. Climate change tends to increase emissions by increasing area burned but decrease them due to decreasing fuel load via faster non-fire decomposition. Increases in CO_2 incude complex responses, on the one hand favouring less flammable shrub vegetation leading to a decrease in area burned, but on the other inducing an increase in fuel load due to faster plant growth. Population change would tend to mostly decrease fire emissions by increasing population in rural areas, especially in the slow urbanisation/high population growth scenario SSP3.

Further results of CO_2 emissions to specific for the current study are shown in the Supplementary Information (Figs. S5 to S7). We note that simulations with LPJ-

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GUESS-SIMFIRE sometimes differ substantially from GFED4.1s (SI Figs. S5, S6). We attribute this to differences in the assumed litter load and combustion completeness between GFED (van der Werf et al. 2010) and SIMFIRE (Knorr et al. 2012). These quantities are generally not well constrained, as noted by Knorr et al. (2012). We expect, however, that the relative change in wildfire emissions, which we compute by country (SI Table S1, Fig. S7), is much less affected by those differences. Deforestation and peat fires are not accounted for by LPJ-GUESS-SIMFIRE and have been excluded form the analysis of impacts on air pollution.

In the following analysis, we show temporal changes in the distribution of emissions by areas of a given population density range because of the central role of human population for both anthropogenic and wildfire emissions (via Equ. 2). Since the areas belonging to each population-density range change over time (see SI Fig. S3), a change in emissions in Fig. 3 can be caused by climate change (wildfires) or due to a given scenario (CLE vs. MFR for anthropogenic), by CO_2-driven increases in woody vegetation leading to lower wildfire frequency (Knorr et al. 2016b), or by a geographic shift in the area that belongs to a given range.

The strongest change in the distribution of wildfire emissions against population density is found for Sub-Saharan Africa under the SSP3/RCP4.5 scenario, where the categories below 10 people per km^2 see a decline in emissions by a factor between 3 and 6 between 2010 and 2090 (Fig. 3 upper left panel). Conversely, areas with more than 100 people per km^2 see a sharp increase in both extent and emissions per area (e.g. Australia). We interpret this as the effect of more people moving into fire-prone area in this slow-urbanisation scenario. Remarkably, the increase in emissions per area is almost completely absent for the SSP5/RCP8.5 scenario across all population density ranges (Fig. 4). As noted by Knorr et al. (2016b), the large increase in

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atmospheric CO_2 associated with RCP8.5 leads to a strong increase in more fire resistant woody vegetation and less emissions, which counteracts the positive effect of climate warming on emissions.

This pattern of increasing wildfire emissions in the most densely populated areas under SSP3/RCP4.5 is seen for all middle to lower-income regions (all but Australia & New Zealand, North America and High-Income Europe, Fig. 3). For South & Southeast Asia and Developing East Asia, a decline in emissions in sparsely populated regions is accompanied by a similar decline in anthropogenic emissions, so that no significant changes in the relative importance of the two emission sources are expected for this particular scenario. For High-Income Europe, wildfire emissions are projected to remain well below anthropogenic air pollutant emissions in all categories, while for Australia & New Zealand, a continuing decrease in emissions in the most densely populated category will make wildfire emissions increasingly relevant in such areas. For North America simulated changes in wildfire are also minor and wildfires will continue to be the dominant source mainly in remote areas.

The situation of relative importance changes drastically if we consider the MFR anthropogenic scenario (Fig. 4). According to this scenario combined with RCP8.5 climate and SSP5 demographic change (rapid urbanisation, but low population growth in low to middle income countries), wildfires could become the dominant emission source in Sub-Saharan Africa and Australia & New Zealand in all population-density categories as early as 2030, and be at least of comparable magnitude as anthropogenic emissions for Latin America & Caribbean and to a lesser extent South & Southeast Asia and Eastern Europe-Russia-Central Asia. High-Income Europe and Developing Middle East & North Africa, who both have the same increasing relationship between emissions and population density for both sources, wildfires will continue to be minor

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in all categories despite strong reductions in anthropogenic emissions. For Developing East Asia, there is an approximately fourfold increase projected for wildfire emissions in the 10 to 100 inhabitants per km^2 category, with the result that they might become comparable to anthropogenic emissions in areas that comprise a rather large population.

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3.3 Future patterns of pollutant exposure

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The wildfire emissions scenario – either SSP5/RCP8.5 with fast urbanisation, low population growth and a high degree of climate change, or SSP3/RCP4.5 with slow urbanisation, high population growth in developing countries and moderate climate change – has a large impact on simulated pollution levels for Sub-Saharan Africa everywhere, except for the most sparsely populated areas (Fig. 5). While both current, and 2090 concentrations under CLE assumptions show a steady increase with population density following the anthropogenic emission changes displayed in Fig. 3, for the MFR anthropogenic scenario the concentration-population density relationship shows a peaked distribution with a maximum in the 1 to 10 people/km^2 range similar to wildfire emissions, either with a moderate (SSP5/RCP8.5, cf. Fig. 3) or a strong decline (SSP3/RCP4.5, cf. Fig. 4) relative to present levels. The distribution of PM2.5 concentrations thus follows that of the summed wildfire and anthropogenic emissions, although – due to atmospheric transport and mixing – with a much smaller relative decline towards the most sparsely populated areas compared to emissions. There is a range of less than one order of magnitude among concentrations in Fig. 5, but about three orders of magnitude among emissions in Figs. 4 and 5. We find that the MFR scenario for Sub-Saharan Africa achieves only moderate declines in pollution levels when combined with the high (SSP5/RCP8.5) wildfire emissions scenario.

For most of the other regions, the difference between the two wildfire emissions scenarios has only little impact on pollution levels (cf. both MFR scenarios in Fig. 5) and the most important factor will indeed be future levels of anthropogenic emissions. For Eastern Europe-Russia-Central Asia, there is a slightly higher concentration for SSP5/RCP8.5 below 0.1 people/km^2, following emissions in this category (cf. Fig. 3 vs. Fig. 4), while emission changes in the other categories do not show up in concentrations due to atmospheric transport and mixing and their small areal extent (i.e. because most of the regions is sparsely populated). Latin America & Caribbean will see either a decrease (SSP3/RCP4.5, Fig. 3) or an increase in emissions (SSP5/RCP8.5, Fig. 4) in the most sparsely populated areas, a difference that is again reflected in the concentrations (Fig. 5). However, a much stronger increase in wildfire emissions with SSP3/RCP4.5 than with SSP5/RCP8.5 in the regions >100 people/km^2 is not reflected in concentrations. This can be explained by horizontal atmospheric transport, because concentrations in the areas with >100 people/km^2 are strongly influenced by cleaner air advected from nearby regions within the 10 to 100 people/km^2 range (see Fig. S3). The 10 to 100 people/km^2 bin (Figs. 3, 4 & S3) has a much larger areal extent and higher emissions per area compared to >100 people/km^2. We must note, however, that the differences in simulated concentrations between the the combined RCP8.5/SSP5-MFR and combined SSP3/RCP4.5-MFR scenarios discussed for these two categories are small.

By contrast, two regions stand out where there is a marked impact of the wildfire scenario on pollution levels in the intermediate range of 1 to 100 people/km^2: South & Southeast Asia, and Developing East Asia. In particular for Developing East Asia, MFR with SSP5/RCP8.5 has a PM2.5 concentration in the 1 to 10 people/km^2 range that is about 3$\mu g/m^3$ higher than the corresponding concentration for SSP3/RCP4.5-

MFR, with the highest difference after Sub-Saharan Africa. For SSP5/RCP8.5, this category has a very strong increase in emissions (Fig. 4). Examination of the corresponding area (Fig. S3) shows that corresponding areas shift from the west to the east and southeast of the region, where fire emissions are much higher (Fig. 1). A similar shift with accompanying increases in emissions is seen for the next higher population-density category as well. The predicted transformation for the SSP5/RCP8.5-MFR scenario of some areas in southeastern China (Fig. S3) towards lower population density coupled with an increase in fire emissions leads to higher pollution levels in the same areas compared to SSP3/RCP4.5-MFR. A similar effect is seen for the South & Southeast Asia region, where there is a general increase in the extent and emission levels of sparsely populated regions under SSP5/RCP8.5-MFR (Fig. 4), which leads to higher pollution levels compared to SSP3/RCP4.5-MFR (Fig. 5) mainly in Southeast Asia and Indonesia. (see Fig. S3; see also areas with high peak-month pollution levels in Fig. 6).

The dominant role of the anthropogenic-emissions scenario for human exposure to PM2.5, evident already in Fig. 5, can also be clearly seen in Table 2. Despite its dominant role in global fire emissions, Sub-Saharan Africa currently only has a rather small fraction of its population subjected to PM2.5 concentrations above 10μg/m^3 annual average from wildfire and anthropogenic emissions. For CLE the percentage value is predicted to more than quadruple, but fall to less than a third or close to zero for MFR.

If we take the highest monthly concentration (note that the WHO air quality guidelines apply to annual mean concentrations, but it is nevertheless useful also to consider monthly values), the picture changes considerably. Not only the highly polluted areas of East and South Asia, but also large parts of Africa and central South

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America experience monthly pollution levels in excess of 20µg/m^3 (Fig. 6). There are also some boreal areas with increasing and high pollution levels for SSP5/RCP8.5-MFR, but they are situated in sparsely populated regions. For South America, peak seasonal exposure above 10µg/m^3 is simulated for between 12% and 2% (SSP3/RCP4.5-MFR, Table 2) of the current and future population, reflecting the fact that the region in central South America is and remains relatively sparsely populated (Fig. S3). Here also, the development of anthropogenic emissions has a much bigger effect on exposure than the wildfire emission scenario. For North America, there is a large region in the northeastern U.S. where peak anthropogenic and biomass burning PM2.5 is above 10µg/m^3 (Fig. 6), with currently 48% of the entire region's population affected, against 0% on an annual basis (Table 2). This area has low wildfire emissions, and therefore the seasonal peak comes from seasonal changes in atmospheric mixing and transport of anthropogenic pollutants, which are assumed to have no seasonal cycle in emissions. However, even for CLE, emissions are predicted to drop considerably (Fig. 3) and peak-month exposure to levels above 10µg/m^3 goes down to zero for all 2090 scenarios (Table 2). For South & Southeast Asia under MFR, the percentage exposed population is not affected by the wildfire emissions scenario (SSP5/RCP8.5-MFR vs. SSP3/RCP4.5-MFR), but for Developing East Asia, there is a marked difference between the two. Increased pollution levels in this region under SSP5/RCP8.5-MFR can be seen mainly in southeastern China (Fig. 6).

4 Discussion

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). An important question is, therefore, whether past climate change has already led to

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increases in wildfire activity and related pollutant emissions (Knorr et al. 2016a). While past climate-driven increases in fire activity remain debatable (Doerr and Santin 2016), this study shows a general picture of climate-driven emission increases that may be overridden by demographic changes only in Sub-Saharan Africa, as shown previously by Knorr et al. (2016b). Southern China is further identified as a new area of high risk from wildfire 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). The simulated decline in Africa is in agreement with observations of declining burned area linked to demographic trends of increasing rural population? for the northern part of Sub-Saharan Africa (Andela and van der Werf, 2014).

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. Therefore, peat and deforestation fires have been excluded from the predictive part of the present study. 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). The comparative analysis shown here, however, shows that globally both are of minor importance for air pollution except for Southeast Asia. The southeast Asian deforestation and peat fires occur mainly in Indonesia (Field et al. 2009), where they are the dominant pollution source and occur even in more densely populated areas. In other world 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 four integrated-assessment model realisations of

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the four RCPs, Hurtt et al. (2011) projected little increase 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).

While any additional emission source of PM2.5 poses a health risk (WHO 2006), in practice 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 sometimes unexpected results of fire suppression policies (Donovan and Brown 2007). However, we find that in large parts of the world, especially where mineral dust is of minor importance, wildfires are the main air pollutant source.

We find that air pollutant concentrations broadly follow the same pattern as 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, a characteristic pattern of wildfire emissions (Sub-Saharan Africa, Latin America & Caribbean, and Eastern Europe-Russia-Central Asia). This means that 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

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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 limit of PM2.5 lower than $10 \mu g/m^3$, WHO also states that health effects persist below these values, and therefore we can assume significant health impacts even if this limit is exceeded only on a seasonal basis.

For certain regions, it will therefore 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 (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.

This study has some important limitations:

- We expect that results will be affected by the presence of natural aerosols, such as mineral dust and seasalt, which depending on location and time of the year could be significant fractions of the PM2.5 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.

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- Transport and emissions of pollutants under future scenarios do not account for possible changes in meteorology.
- The anthropogenic emission scenarios do not consider the benefits of climate mitigation scenarios, and are based on rather crude assumption regarding the development of emissions controls beyond 2050.
- The demographic scenarios used do not currently account for changes in the urban mask.
- The study only considers climatological annual emissions during specified time windows, even though wildfire impacts on air quality can have large interannual (Jaffe et al. 2008) and intra-seasonal variations.
- Our study does not account for relevant secondary emission products, such as ozone from wildfires, which can reach policy-relevant levels (Jaffe and Wigder 2012). This contrasts with previous 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.

This is the first global-scale 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

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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 PM2.5 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 PM2.5 limit of 25 μg/m^3 (WHO 2006) is a exceeded as a result of wildfire emissions.

5 Summary and conclusions

- Globally, the percentage of world population exposed to dangerously high PM2.5 emissions from wildfires is expected to decrease in all scenarios considered. The future of anthropogenic emissions has the largest impact, and for a scenario of current legislation, the predicted decrease is very small.
- 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, there will be large decreases in emissions in many parts of the continent. Exposure of humans to PM2.5 in Sub-Saharan Africa is expected to drop if measures are put in place to reduced anthropogenic emissions, but wildfires may remain a health relevant pollution sources in a scenario of fast urbanisation and slow population growth.
- In a number of regions, wildfire emissions will remain 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.

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Deleted: <#>So far, there does not seem to be compelling evidence for a long-term trend towards increased pollutant emissions from wildfires due to climate warming. While in the Western U.S. burned area from wildfires seems to have increased and the increase may be linked to climate, the present study simulates only very small relative increase for the region. Most of the predicted increase for North America concerns the boreal forest zone.

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Deleted: for all demographic scenarios, but mostly for high population growth and slow urbanisation. Stronger fire suppression by higher rural population outweighs the effect of larger populations in rural areas.

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Deleted: <#>Globally, both the number of people and the percentage of world population exposed to dangerously high PM2.5 emissions from wildfires is expected to increase in all scenarios considered. Both relative and absolute increase are highest for high population growth, while the degree of urbanisation plays only a minor role. This is opposite to the average fractional burned area in densely populated regions – a measure of fire risk to properties and lives – where the projected increase was earlier found to depend mostly on the degree of urbanisation. ... [13]

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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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