FINAL REPORT

Estimating the Effects of Changing Climate on Fires and Consequences for U.S. Air Quality, Using a Set of Global and Regional Climate Models

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iii. Abbreviations/Acronyms

$PM_{2.5}$: particulate matter less then 2.5 microns in diameter

O_3 : Ozone

MDA-8: the daily maximum 8 h average of surface O_3

CESM: Community Earth System Model

CLM: Community Land Model

CAM-Chem: Community Atmospheric Model with chemistry

RCP: Representative Concentration Pathway

SSP: Shared Socioeconomic Pathways

iv. Keywords

model simulations; predictions; earth system model; fire module; fire area burned; future air quality; ozone; $PM_{2.5}$

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Abstract

Emissions of aerosols and gases from fires have been shown to adversely affect US air quality at local to regional scales as well as downwind regions far away from the source. In addition, smoke from fires negatively affects humans, ecosystems, and climate. Recent observations have shown an upward trend of area burned over western US resulting from increasing fire activity, most likely related to climate change. Climate-driven changes in fire emissions may result in an increase of carbonaceous aerosol, and a significant increase in annual mean $PM_{2.5}$ and haze.

This project provided an integrated assessment of the effects of fires under different future climate and population scenarios on fine particulate matter mass ($PM_{2.5}$) and ozone (O_3) at global scale, with a particular focus on the United States. The objectives of this study, most of which were met, were: 1) use of climate projections to predict changes in fire activity in 2050, 2) identify potential changes in vegetation and fuels resulting from changes in climate and their implications in fire activity, 3) identify changes in fire occurrence and severity resulting from changes in future climate and vegetation and fuels, and 4) predict impacts on air quality resulting from changes in fire activity and climate on the mid-21st century.

We employed the global Community Earth System Model (CESM) with the RCP climate, anthropogenic emissions and land use, and the SSP population projections (i.e., RCP4.5/SSP1 and RCP8.5/SSP3). Within CESM, we used a complex-based fire parameterization to project future climate- and human-driven fire emissions, and considered landscape, deforestation, agricultural and peat fires.

Our study showed that on a global scale fire area burned is predicted to increase about 8% in 2050 and 30% at the end of the 21st century compared to present day as a result of climate and population density changes. When we isolated climate changes, we found more dramatic increases in area burned throughout the century, with 20-30% in 2050 and 28-77% in 2100, which shows the important role that fire suppression may play on a regional scale. Across the world, $PM_{2.5}$ concentrations are predicted to increase significantly as a result of increased fire activity. These increases are most prominent over North America, EuroAsia and Equatorial regions, in which fire-driven $PM_{2.5}$ may potentially offset anticipated reductions in anthropogenic emissions. During the summertime, fire emissions will dominate $PM_{2.5}$ concentrations almost entirely across the US. The number of annual mortalities attributed to $PM_{2.5}$ as well as visibility degradation are similar to the $PM_{2.5}$ changes, with increases in fire $PM_{2.5}$ offsetting benefits from anthropogenic $PM_{2.5}$ reductions. Changes in fire emissions will also significantly impact future O_3 air quality, with increases up to 9 ppb to the daily maximum 8-hour average over western US. Our study illustrates the need to consider the effects of fires in future air quality management and planning and emission policy making, as controlling anthropogenic emissions may not be enough to attain future air quality targets.

1. Background

About 500 million hectares of vegetated land burn around the world every year, either in the form of wildfires ignited by accident or by natural causes (e.g. lightning) or prescribed fires used for agricultural and ecological control [e.g., van der Werf et al., 2010]. Fires emit large amounts of smoke, which is composed of aerosol particulate matter (PM), such as black carbon (BC), and numerous trace gases (e.g., CO_2, CO, NO_x).

Smoke from fires negatively affects humans, ecosystems, and climate. Exposure to smoke has been associated with increased eye and respiratory symptoms, bronchitis, asthma and mortality. Smoke particles with aerodynamic diameter below 2.5 μm ($PM_{2.5}$) are particularly toxic since they can penetrate into the lungs, with effects from even a single exposure [e.g., Pope et al., 2006]. For example, during the El Niño 1997 dry season, peat fires in Indonesia resulted in 10,000 excess deaths from smoke exposure [Marlier et al., 2013]. In addition, smoke pollutants can be transported hundreds of kilometers downwind. For example, in May 2016, a massive smoke plume generated from the Fort McMurray fire in Canada crossed Greenland and reached Spain. This long-distance smoke can adversely affect visibility in pristine regions [e.g., Val Martin et al., 2013], and accelerate Arctic warming [Stohl et al., 2007]. Fires can also have devastating effects, e.g., the February 2009 Black Saturday bushfires in Australia killed more than 200 people and destroyed about 1,000 houses.

Fire activity is strongly linked to climate and humans. Observations over the western United States (US) and Canada have shown an upward trend of fire frequency over the past 25 years due to higher temperatures and earlier snowmelt [e.g., Westerling et al., 2006], and tropical fires in equatorial Asia have increased by about 280% from 1990 to 2010 due to rapid palm oil plantation development [e.g. Carlson et al., 2013]. However, in many other regions observations of area burned have revealed a long-term declining trend as a result of fire prevention, fire-fighting efficiency and expansion of croplands [Doerr and Santin, 2016].

Meteorological conditions, such as high temperature, low precipitation, and low relative humidity, affect the extent of area burned by fires [e.g., Westerling et al., 2006]. In addition, meteorological conditions experienced during the months or years preceding the fire may influence the amount of fuel and fuel moisture, which in turn can significantly affect the area burned [e.g., Westerling et al., 2006]. On the other hand, land-use management and fire suppression may help reduce wildfire severity, while deforestation and agriculture fires may increase fire activity [Doerr and Santin, 2016]. Addressing these concerns requires coupling climate, vegetation and fire models as well as a comprehensive understanding of the multiple interactions among fires, climate, vegetation, and people.

This project provides an integrated assessment of the pollution and associated health effects of fires under different future climate and population scenarios on fine particulate matter mass ($PM_{2.5}$) and ozone (O_3) at global scale, with a particular focus on the United States. We employ the global Community Earth System Model (CESM) with the IPCC Representative Concentration Pathway (RCP) climate, emissions, and land use projections. Within CESM, we use a complex-based fire parameterization [Li et al., 2012] to project future climate-driven and human-caused fire emissions, and study the current and future impact on fire pollution on air quality.

2. Objectives and Hypothesis

This project addressed Task 1*, Climate change and wildfire smoke at regional scale: Vegetation, fuels, fire regimes, and air quality impacts,* within the JFSP Framework No. FA-FON0013-0001. Following Task 1, our project simulated fuels, wildfire regimes, and smoke impacts resulting from projected future scenarios of climate change and associated altered ecosystems, and studied the potential impact of climate change on wildfire smoke and emissions. The following objectives and hypotheses were proposed:

Objective 1. Use of climate projections to predict changes in fire activity in 2050. *This objective was met, with some modifications.* We used CESM with a fire module and the RCP4.5 and RCP8.5 climate projections, without any downscaling, to bracket the range of possible future fire regimes. We performed the simulations at a 100x100 km horizontal resolution, instead of the proposed 50x50 km due to model availability issues. In addition, we expanded the simulations to 2100, incorporated the effect of deforestation and peat fires and studied the contribution of future population changes on fire activity. Furthermore, we extended the study to other fire regions across the world, beyond North America.

Objective 2. Identify potential changes in vegetation and fuels resulting from changes in climate and their implications in fire activity. *This objective was partially met.* We focused on the different type of fires, from landscape, deforestation, peat and agricultural fires. A full identification of changes in vegetation and fuels resulting from climate was not possible due to time constrain as we decided to focus on human health impacts that were not initially proposed but add information to the estimation of future smoke (see section 4.5).

Objective 3. Identify changes in fire occurrence and severity resulting from changes in future climate and vegetation and fuels. *This objective was fully met.* We simulated fire activity across the 21st century using a fire module embedded in a global dynamic vegetation model driven by climate and population, the main drivers of fire. We were able to obtain a variability of fire regimes across different decades, and accounted for low and high fire active years in our analysis.

Objective 4. Predict impacts on air quality resulting from changes in fire activity and climate on the mid-21st century. *This objective was fully met, with some modifications.* We applied CESM to study the effect of increased fire activity on global air quality, and quantified surface $PM_{2.5}$, O_3 and visibility in present-day and future over the continental United States. In addition, we isolated changes in fire pollution resulting from fires alone, and also from the main fire drivers, i.e., climate and population changes. We examined if output from CESM could be used with the high-resolution regional model WRF-Chem, instead of the proposed PMCAMx.

Hypothesis 1. Projected climate changes will increase fire occurrence and severity over the US by 2050. Our simulations confirmed that climate change will increase fire area burned across the continental US as well as many other regions across the world.

Hypothesis 2. Vegetation and fuels over the US will significantly respond to changes in climate. We did not address this hypothesis specifically due to time constrains. However, we determined that different type of fires (peat, agricultural, landscape) will respond to changes in climate and population.

Hypothesis 3. Changes in fire activity in the future will adversely affect air quality over the

US. Our project confirmed that increased fire emissions in the US will negatively affect air quality ($PM_{2.5}$, visibility, and surface O_3). For example, in 2100, fire emissions will dominate summertime $PM_{2.5}$ concentrations almost entirely across the US and fire pollution alone will contribute up to 9 ppb of surface summertime O_3 MDA-8 over western US.

Hypothesis 4. Increased future fire emissions will offset the air quality benefits of future anthropogenic emission reductions. Our simulations confirmed that fire emissions will offset the benefits of future anthropogenic emission reductions in many regions across the world, in particular over the populated regions of North America and Europe.

Hypothesis 5. The global 50 km x 50 km simulations of the CESM model accurately predict present-day fire activity and air quality at a regional scale. We were not able to compare our global simulations with CESM (100x100 km) with the high-resolution output from WRF-Chem (12x12 km) to examine if the global CESM model could resolve the effect of fire activity on air quality at regional scale due to differences in meteorology between the simulations (see Section 4.6). However, from our detailed model evaluation, we are confident that CESM accurately predicted present-day fire activity and air quality at a regional scale.

3. Methodology

3.1 Global Modeling Work

To quantify the effects of potential changes in fire activity on air pollution over the 21st century, we used CESM (http://www2.cesm.ucar.edu) with an integrated fire scheme. CESM is a fully coupled chemistry-climate-land model, which includes atmospheric, land, ocean and sea ice models that can be run in stand-alone and coupled configurations.

To simulate land surface processes, we used the Community Land Model (CLM) version 4.5, which is part of CESM. CLM4.5 uses a global dynamic vegetation model with carbon and nitrogen biogeochemistry, vertically resolved soil C, and nitrification/denitrification [CLM4.5-BGC] to treat the response of vegetation to future climate and fires. CLM4.5-BGC also includes a prognostic treatment of fires based on a modified version of the fire algorithm by Li et al. [2012, 2013]. The fire algorithm accounts for agricultural, deforestation, peat and landscape fires, and estimates area burned and fire emissions using information about climate, vegetation, land cover-land use (LCLU) changes, gross domestic product (GDP) and population density (Figure 1).

For the atmospheric model, we used the Community Atmospheric Model (CAM) version 4 fully coupled with an interactive gas-aerosol scheme (CAM-Chem) [Lamarque et al., 2012]. CAM-Chem's chemical mechanism contains full tropospheric chemistry, including O_3, NO_x, SO_x, CO, VOC oxidation processes, and a bulk aerosol scheme including sulfate, ammonium nitrate, carbonaceous aerosols, SOA, sea salt, and dust. Major biogenic VOC species are calculated within CLM4.5 using MEGANv2.1 and transferred into the chemical mechanism of CAM-Chem.

We run CESM version 1.2 with online computed meteorology and prescribed sea-surface and sea-ice distributions, corresponding to previous fully coupled simulations. Simulations were performed at the horizontal resolution of 100x100 km, and vertical resolution of 26 layers from the surface to about 4 hPa, with a time step of 30 min. In collaboration with NCAR, we coupled the fire module embedded in CLM4.5 to the atmospheric model CAM-Chem, and implemented

the most-up-to-date fire emission factor inventory based on field and laboratories studies [Akagi et al., 2011, 2013; Yokelson et al., 2013] to estimate fire emissions.

Our first evaluation of the CESM fire module showed that fire area burned over the North America and Siberia boreal regions was significantly underestimated in our simulations. The issue resulted from a combination of a bias in precipitation from CAM and soil moisture from CLM over those regions. To avoid this bias, we designed a slightly different set of experiments: first, we run the fire module with CESM CLM offline using atmospheric forcings to produce fire emissions, and second we transferred the fire emissions into the atmospheric chemistry model CESM CAM-Chem to determine air quality impacts (Figure 1).

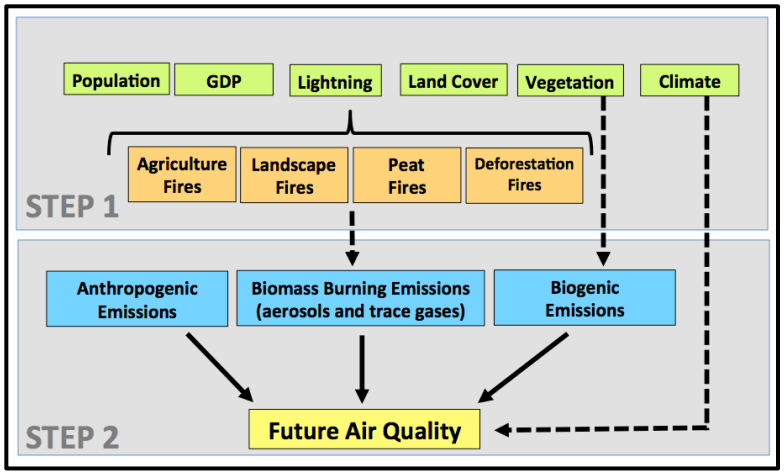

Figure 1. Simple diagram of the fire modeling framework.

In Step 1, we predicted fire area burned and fire emissions. Table 1 summarizes the different fire experiments. We did a transient run of CLM4.5-BGC with the fire module from 1850-2005 forced with atmospheric data from the Climatic Research Unit of the National Centers for Environmental Prediction (CRUNCEP), and population data from the History Database of the Global Environment (HYDE). Future fire simulations (2006-2100) were performed using monthly climate anomalies from previous CESM1 simulations with the RCP4.5 and RCP8.5 scenarios. To study the contribution of human intervention on fire activity as a result of fire suppression and/or ignition, we designed two experiments: First, we used population density changes predicted from the Shared Socioeconomic Pathways (SSPs). The SSP scenarios describe the interaction of climate change scenarios with social, economical, and political changes in terms of mitigation and adaptation. We combined SSP and RCP scenarios following van Vuuren and Carter [2014]: RCP4.5+SSP1 and RCP8.5+SSP3. This allowed to bracket our results, ie., we used a stabilization scenario (RCP4.5) with a low growth, sustainable world (SSP1), and the largest forcing scenario (RCP8.5) with a high population, fragmented world (SSP3). Second, we included two simulations in which we kept population changes constant to year 2000 (present-day).

Table 1. List of fire simulations in Step 1.

Simulation	Climate & Time Period	Population & Time Period
2000	CRUNCEP 1850-2005	HYDE 1850-2005
RCP45	RCP45 2006-2100	HYDE 2000
RCP45/SSP1	RCP45 2006-2100	SSP1 2006-2100
RCP85	RCP85 2006-2100	HYDE 2000
RCP85/SSP3	RCP85 2006-2100	SSP3 2006-2100

In Step 2, we completed 8 modeling experiments with CAM-Chem, summarized in Table 2. Each model simulation was initialized in 2000, 2040 and 2090 with a 1-year spin-up run. Following initialization, present-day and future ‘‘snapshot’’ climate simulations were performed for 10 years. We kept anthropogenic and biogenic emissions constant to 2000, 2050 and 2100, and used 10-year periods for the fire emissions to consider a wide range of fire regimes within each decade (i.e., 1995-2005, 2040-2050 and 2090-2100, respectively). We then averaged the results and used all years to evaluate interannual variability and ultimately define statistical significance. We replicated these simulations for the RCP4.5 and RCP8.5 and RCP4.5/SSP1 and RCP8.5/SSP3 scenarios. To determine the contribution of fire pollution on air quality, we included a set of simulations in which fire emissions were not included (“No Fire”). To compare the contribution of fire pollution from the continental US to fire pollution from the neighboring countries of Canada and Mexico, we included another simulation with RCP8.5/SSP3 in which we turned off fires in Canada and Mexico (not shown in Table 2).

Table 2. List of fire simulations in Step 2

Simulation	Fires	Anthropgenic	Biogenic	Climate	LCLU
2000	1995-2005	2000	2000	2000	2000
2000 No Fire	--	2000	2000	2000	2000
2050[a]	2040-2050	2050	2050	2050	2050
2050 No Fire	--	2050	2050	2050	2050
2100[a]	2090-2100	2100	2100	2100	2100
2100 No Fire	--	2100	2100	2100	2100

[a] 2050 and 2100 were performed for RCP4.5, RCP8.5, RCP4.5/SSP1 and RCP8.5/SSP3

As a first step in the quality control of the model estimated fire activity, we evaluated fire area burned and main fire emissions from the CESM-fire offline setting against GFEDv4 (Figure 2). We found that CESM-fire offline captures well the spatial distribution and magnitude of fire area burned, including over the boreal regions. For example, the relationship between global annual fire area burned in CESM and GFEDv4 has a normalized mean bias (NMB) of 1.5% and r^2 of 0.7. Over North America, the fire module slightly overestimates area burned compared to GFEDv4, and underestimates it over Africa and Australia (Figure S1 in Appendix D). In terms of fire emissions, we found that the fire module in CESM reproduces well the magnitude of the main fire species (Figure 3).

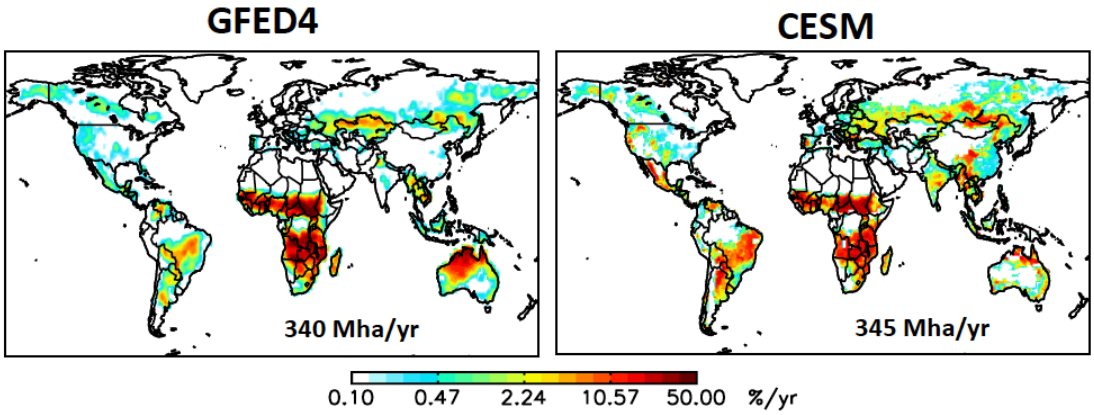

Figure 2. Spatial distribution of annual area burned (%/yr) averaged over 1995-2005 for GFED4 and CESM. Total global area burned (Mha/yr) are provided in the inset.

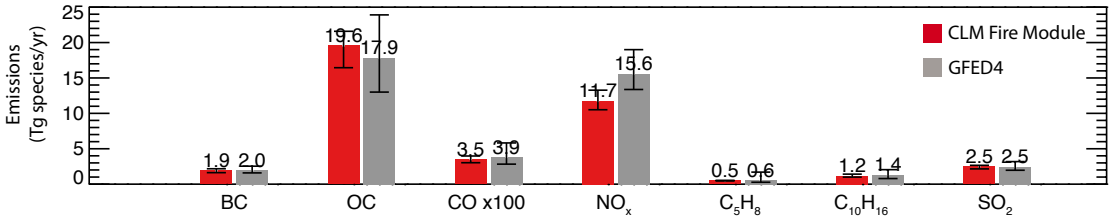

Figure 3. Global annual fire emissions (Tg species/yr) for main fire species averaged over 1995-2005 for GFED (grey) and CESM-CLM fire module (red). Fire emissions are: black carbon (BC), organic carbon (OC), carbon monoxide (CO), nitrogen oxides (NO_x), isoprene (C_5H_6), monoterpenes ($C_{10}H_{16}$) and sulfur dioxide (SO_2).

In addition, to assess how well our model represents key air pollutants at present-day with the newly created fire emissions, we evaluated our baseline simulations (year 2000) of $PM_{2.5}$ with global observations compiled in van Donkelaar et al., [2015] (Figure 4). In more detail, we also evaluated our simulations over the United States using long-term means (1995-2005) of $PM_{2.5}$ and its main chemical species (BC, OC, SO_4 and NH_4NO_3) from IMPROVE, and O_3 from CASTNET (Figures S3 and S4 in Appendix D). We found that CESM simulates well the spatial distribution of surface $PM_{2.5}$ concentrations, although somewhat underestimates $PM_{2.5}$ over Asia. Over North America, we found that the annual levels are well represented (r^2=0.6 and slope=1.1). Annual NH_4NO_3 and organic aerosols concentrations are slightly overestimated, whereas SO_4 is underestimated. Annual BC, dust and sea salt concentrations showed good agreement with the mean observations. For O_3, we found that simulated surface summertime concentrations are in good agreement with the mean observations over eastern and western US (r^2=0.4 and 0.8, respectively).

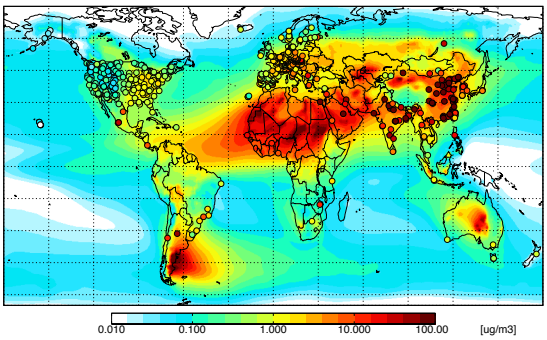

Figure 4. Simulated and observed present-day surface $PM_{2.5}$. Observations over United States and Europe are long-term means from the IMPROVE and EMEP networks. Over the rest of the world, observations are averages from literature compiled data (van Donkelaar et al., 2015).

3.2 Regional Modeling Work

We had originally planned to determine regional changes in PM due to changes in wildfire emissions using WRF-Chem. We did several different test simulations to determine the usefulness of this endeavor (discussed further in Section 4.6). For these simulations, we ran WRF-Chem over the continental US at a 36 km resolution for several different years. We used the FINN [Wiedinmyer et al., 2011] emission inventory for testing the meteorology and fire emission resolution. In our simulations, we used the Global Forecast System (GFS) meteorology and reinitialized each day. Concentrations were output for each model hour, which we then averaged to provide daily 24 h average surface concentrations.

4. Results and Discussion

4.1 Changes in fire activity

Using results from the fire simulations produced in Step 1, we investigated the changes in fire activity across the 21st century. Simulated changes in fire area burned are driven by the complex interaction of climate change, human activities and changes in vegetation cover. Figure 5 shows the time series of global area burned from 1995 to 2100. Decadal averages are also shown for clarity. We found that global area burned may increase about 8% in 2050 and 30% at the end of the 21st century compared to present day as a result of climate and population density changes (RCP4.5/SSP1 and RCP8.5/SSP3). When we isolated climate changes, we found more dramatic increases in area burned throughout the century, with 20-30% in 2050 and 28-77% in 2100, which shows the important role that fire suppression may play. On a regional scale (Figure S5 in Appendix D), we found that human fire suppression will be particularly important over Africa (NHSA and SHSA). For example, fire suppression may reduce fire area burned by a factor of 2 or more on the fragmented world population projection (RCP8.5/SSP3). Over United States, the effect of population changes is negligible, as this is a region already densely populated at present-day.

Similar results were obtained on total fire carbon emitted, although the influence of demographic changes is not as noticeable as for area burned. The reason is that fuel carbon content, a main component for total fire carbon emissions, is small over Africa, as compare to other regions.

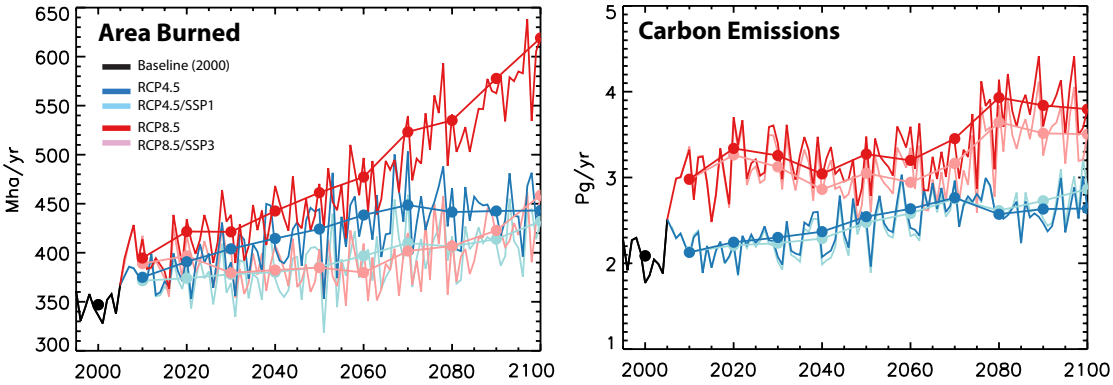

Figure 5. Annual global area burned and total carbon emissions from 1995 to 2100. Decadal averages (solid circles) are shown for clarity.

4.2 Effects on future air quality

Changes in fire activity can be an important factor controlling future $PM_{2.5}$ concentrations in many regions across the world. We used the fire emission projections within CAM-Chem to analyze the effect in $PM_{2.5}$ across different continental-scale fire regions identified in Figure 6. Figure 7 shows the effect of fire emissions on annual $PM_{2.5}$ across these regions.. We show the $PM_{2.5}$ levels predicted by the RCP scenarios in 2050 and 2100 due to fire emissions and those from other sources (i.e, anthropogenic and biogenic), and focus on fire predictions resulting from changing in climate and population (i.e., RCP4.5/SSP1 and RCP8.5/SSP3). We include global distribution maps in Figure S5 in the Appendix D. Consistent with previous studies [e.g., Fiore et al., 2012, Val Martin et al 2015], we found that reductions in anthropogenic emissions projected by RCP4.5 and RCP8.5, combined with land use and climate changes, will lead to a decrease in $PM_{2.5}$ concentrations across the world, except in Africa, South America, Middle East and Australia. For example, over the lower 48 states (TENA), annual $PM_{2.5}$ concentrations will be reduced by half by the end of the century, as predicted by both RCP4.5 and RCP8.5 scenarios. However, $PM_{2.5}$ concentrations may increase significantly as a result of increased fire activity. These increases are most prominent over North America, EuroAsia and Equatorial regions, in which fire-driven $PM_{2.5}$ may potentially offset anticipated reductions in anthropogenic emissions. These regions are also densely populated. For example, over Europe, we estimate that fire activity may contribute to 30% of $PM_{2.5}$ levels in 2050 and about 50-60% in 2100.

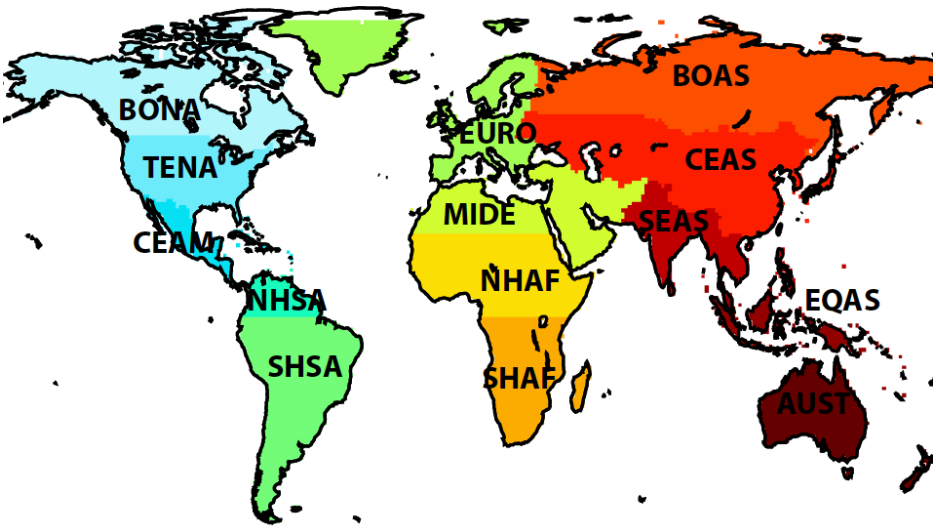

Figure 6. Fire region map based on GFED [van der Werf et al., 2010]. Different continental-scale regions are as follows: Boreal North America (BONA), Temperate North America (TENA), Central America (CEAM), Northern Hemisphere South America (NHSA), Southern Hemisphere South America (SHSA), Europe (EURO), Middle East (MIDE), Northern Hemisphere Africa (NHAF), Southern Hemisphere Africa (SHAF), Boreal Asia (BOAS), Central Asia (CEAS), Southeast Asia (SEAS), Equatorial Asia (EQAS), and Australia (AUST).

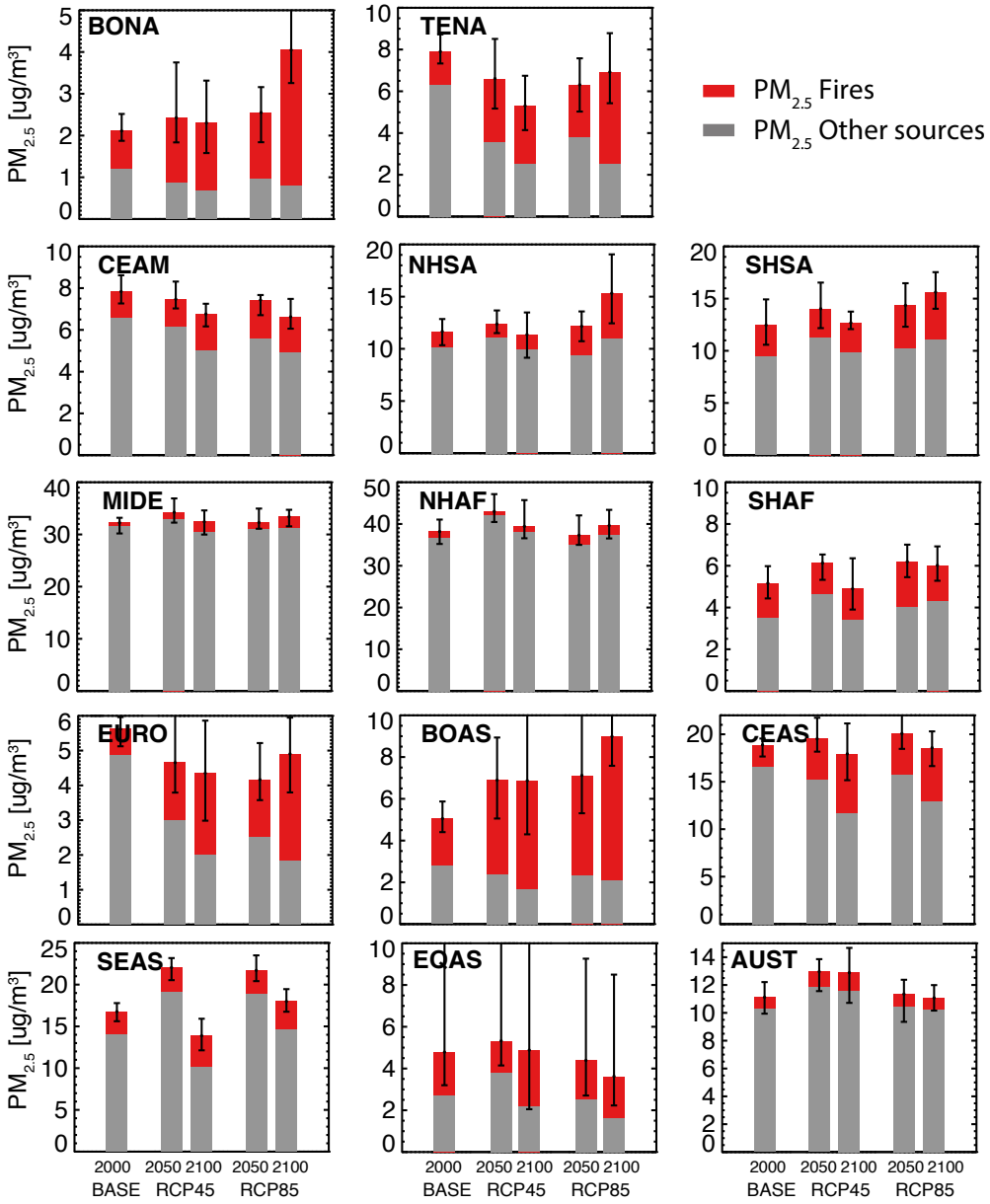

Figure 7. Annual changes in $PM_{2.5}$ resulting from fire activity driven by climate and population changes (RCP4.5/SSP1 and RCP8.5/SSP3) in the fire regions shown in Figure S2. $PM_{2.5}$ concentrations from fires are shown in red and from other sources (anthropogenic and biogenic) in grey.

4.3 Isolated effects of population and climate changes on fire pollution

We quantified the relative contribution of climate and humans to future fire pollution. For that we determined the percentage of fire PM2.5 resulting from changes in climate and humans via fire ignition (+ effect) or suppression (- effect). Figure 8 summarizes results across the 21st century and over the different fire regions. It is obvious that future fire pollution will be primarily driven by climate across the entire century regardless of the fire region and projection. The contribution of human intervention on fire pollution, although minor compared to climate,

can be significant in some regions. For example, the RCP8.5/SSP3 scenario projects that over southern Africa fire suppression, or less fire ignitions, can help reduce $PM_{2.5}$ concentrations by 60% in 2100, counteracting the increase in $PM_{2.5}$ from fire pollution resulting from climate change. On the opposite effect, the RCP4.5/SSP1 scenario projects the increase in $PM_{2.5}$ concentrations from fires over Europe will be also driven by human fire ignitions, in addition to climate change.

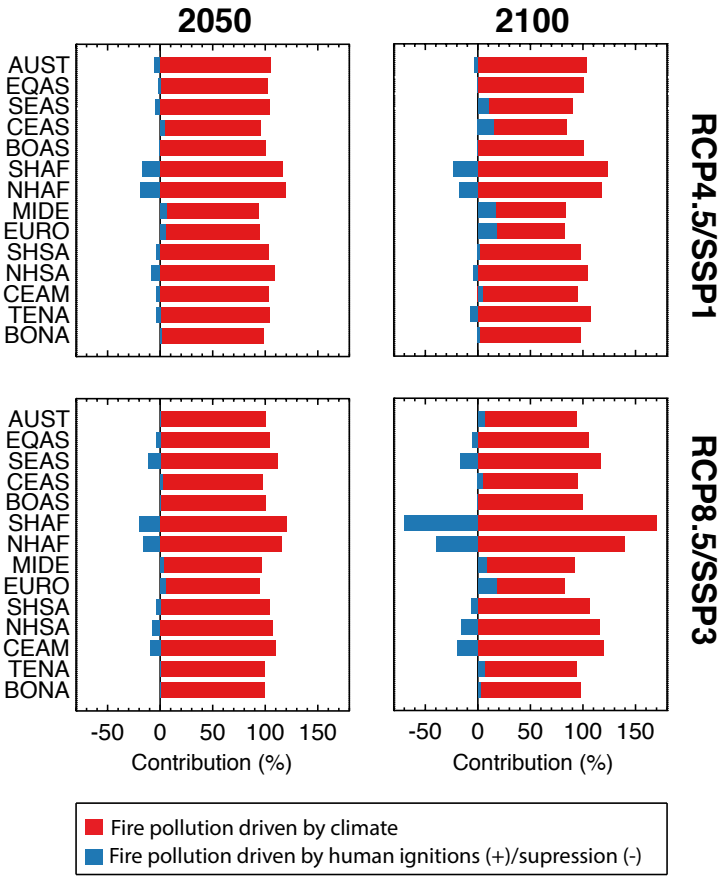

Figure 8. Contribution (in %) to the annual fire $PM_{2.5}$ concentrations of the main individual drivers for the RCP4.5 and RCP8.5 scenarios and across the different fire regions (Figure 6). Bars represent climate (red) and humans via fire suppression/ignition (blue).

4.4 Fire impacts on summertime air quality over the United States

Emissions of aerosols and gases from wildfires have been shown to adversely affect air quality during the summertime over the US. We analyzed changes in $PM_{2.5}$, visibility and ozone (O_3) as a result of future fire activity in the continental US.

Figure 9 presents changes in $PM_{2.5}$ concentrations during the US fire season (May-October) across the US. Similar to Figure 6, we show $PM_{2.5}$ levels from fire emissions and other sources predicted by the RCP4.5/SSP1 and RCP8.5/SSP3 scenarios in 2050 and 2100. Results are presented clustered in six climatic regions defined in Figure S6 in Appendix D. Our analysis

showed the important decrease in future $PM_{2.5}$ across the US as a result of strong anthropogenic emission reductions predicted by RCP4.5 and RCP8.5 scenarios. This is consistent with previous studies [e.g.,Val Martin et al., 2015]. When we considered $PM_{2.5}$ changes including fire emissions, we found that $PM_{2.5}$ concentrations will increase significantly as a result of increased fire activity, and in fact fire emissions will dominate summertime $PM_{2.5}$ concentrations almost entirely across the US. For example, over the West region we estimate that, by the end of the century, fire activity may increase future summertime $PM_{2.5}$ from 2 to 9.5 μgm^{-3} in the RCP4.5/SSP1 scenario and from 1.8 to 11.2 μgm^{-3} in the RCP8.5/SSP3 scenario.

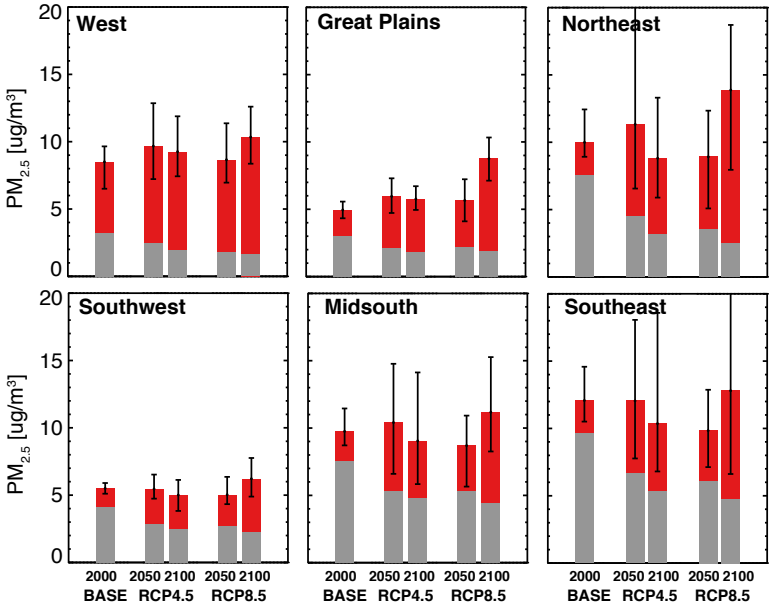

Figure 9. Summertime changes in $PM_{2.5}$ resulting from fire activity driven by climate and population changes (RCP4.5/SSP1 and RCP8.5/SSP3) across different US regions. $PM_{2.5}$ concentrations from fires are shown in red and from other sources (anthropogenic and biogenic) in grey.

To assess changes in visibility, we used the updated visibility equation from IMPROVE (http://vista.cira.colostate.edu/Improve/the-improve-algorithm/). This equation calculates light extinction, which gets converted into a Haze Index [US EPA, 2003] and Visual Range [Pitchford and Malm, 1994].

$$b_{ext} \approx 2.2 \times fS(RH) \times [Small\ Ammonium\ Sulfate] + 4.8 \times fL(RH) \times [Large\ Ammonium\ Sulfate] + 2.4 \times fS\ (RH) \times [Small\ Ammonium\ Nitrate] + 5.1 \times fL(RH) \times [Large\ Ammonium\ Nitrate] + 2.8 \times [Small\ Organic\ Mass] + 6.1 \times [Large\ Organic\ Mass] + 10 \times [Elemental\ Carbon] + 1 \times [Fine\ Soil] + 1.7 \times fSS(RH) \times [Sea\ Salt] + 0.6 \times [Coarse\ Mass] + Rayleigh\ Scattering\ (Site\ Specific) + 0.33 \times [NO_2\ (ppb)]$$

In Figure 10, we show the changes in visibility on the 20% worst and 20% best days as expected by 2050 and 2100 from the simulations including fires (left) and simulations without fires (right). Without fires, there would be an improvement in visibility across the CONUS for the best and worst days. These improvements would be seen by 2050 and continue on to 2100. However, as

some of the worst visibility days are due to the presence of wildland fire smoke, the simulations which include smoke show that visibility on these days could actually could get worse (even though the baseline concentrations are decreasing). This is both an issue in the western US which experiences wildfires and in the southeastern US which has a lot of agricultural burning as well.

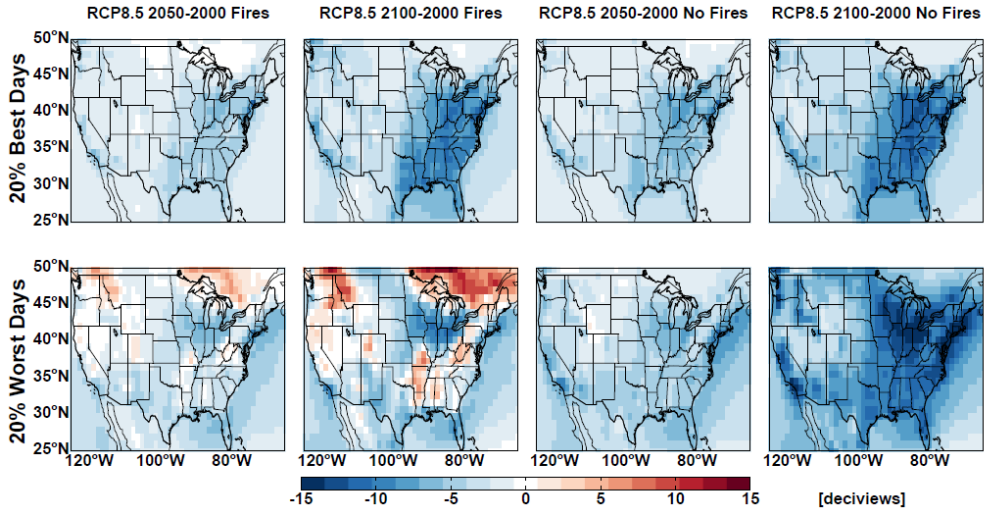

Figure 10. Projected changes in the 20% best and 20% worst visibility days by 2050 and 2100 compared to 2000 for simulations with fire emissions and without fire emissions.

Figure 11 shows the cumulative distribution of visibility at 2 IMPROVE sites, as an example. We show that visibility degradation will be more due to fires in the future than currently. This is shown by the spread between the simulations with fire and without in the different time periods. In the current time (2000s), there is some difference between the simulations, but the gap widens by 2050 and 2100. Most of the visibility degradation from smoke is due to CONUS fires, rather than transported smoke (shown by difference between simulations with fires and simulations with only CONUS fires) with the exception of a few sites in Minnesota, Michigan, and New England.

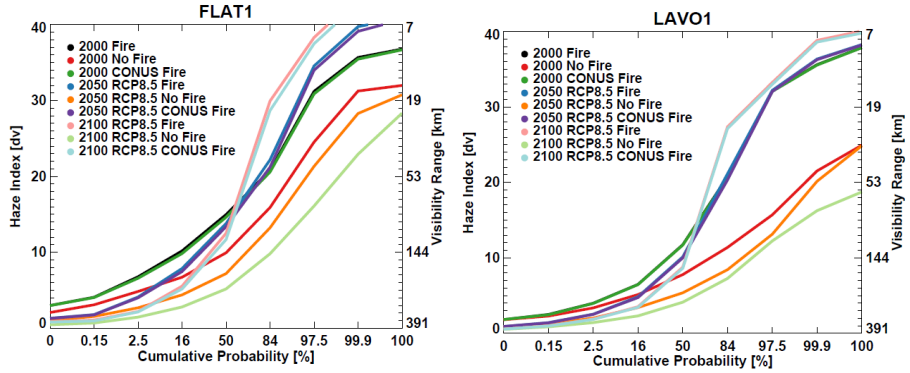

Figure 11. Cumulative distribution plots for visibility in 2000, 2050, and 2100 at the FLAT1 IMPROVE site in northwestern Montana (left) and the LAVO1 site in northern California.

For ozone, we focused on the daily maximum 8 h average (MDA-8), the US EPA metric for air quality standard. Figure 12 shows changes in future MDA-8 across the century as predicted by the RCP4.5/SSP1 and RCP8.5/SSP3. To assess the overall impact of fire emissions on the O_3 levels, we also included the changes in MDA-8 without fires. Consistent with previous studies [e.g., Val Martin et al., 2015], the RCP4.5 scenario predicts a strong decrease in surface O_3 across the continental US, with the strongest absolute reductions over the eastern US and California (> 20 ppb by 2100). The RCP8.5 scenario predicts marginal decreases (about 2 ppb) over the eastern US and California and important increases over the Great Plains region (about 5 ppb). Changes in fire emissions alone will also significantly impact future O_3 air quality. When fire emissions are considered in the simulations, simulated surface O_3 increases by 4 and 5 ppb across the US in the RCP8.5 and RCP4.5 scenarios, respectively, with the largest absolute changes over the western US (up to 8 and 9 ppb, respectively).

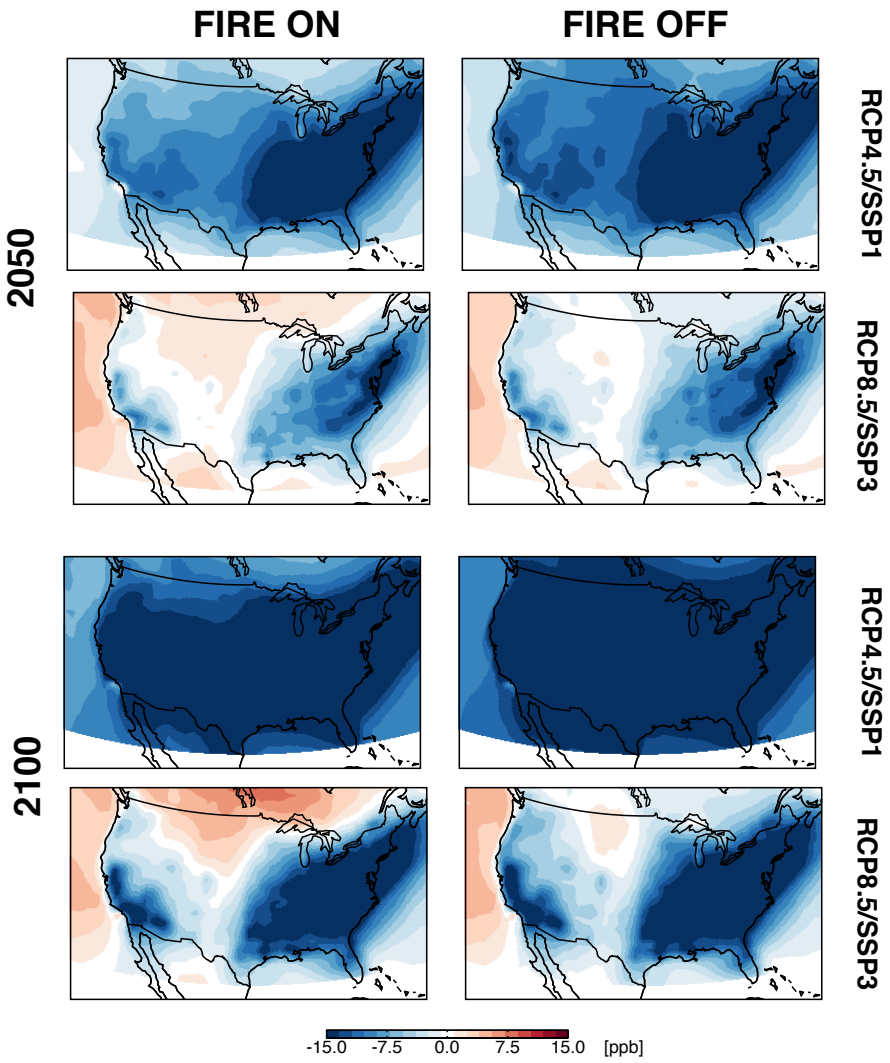

Figure 12. Projected simulated 2050–2000 and 2100-2000 changes in summertime O_3 MDA-8 as a result of the combination of climate, land use and emission changes for the RCP4.5/SSP1 and RCP8.5/SSP3 scenarios, with fire emissions on and off.

4.5 Health effects of future fires over the United States

We calculated the all-cause mortality associated with changes in the annual-average concentrations in $PM_{2.5}$ from the global CESM simulation with the RCP8.5 scenario. We use the following concentration response function:

$\Delta Mort = y_0(1-exp^{-\beta\Delta X})*population$ [Anenberg et al., 2010].

In the equation, for the beta coefficient (ß), we use results from Pinault et al. (2016). For baseline mortality, we use the SSP3 population projections, and we use the US national average death rate for all-cause mortality for each year in our simulation time period. Population is on a 0.5° resolution grid; therefore, we regrid the $PM_{2.5}$ concentrations to the same 0.5° resolution as the population to estimate exposure concentrations.

We calculated the burden for 2000, 2050, and 2100 for the simulations with fires, without fires, and with only CONUS fires (emissions in Canada, Mexico, and Alaska turned off). As shown in Figure 13, we find that the overall number of deaths associated with $PM_{2.5}$ exposure will decrease (which is largely due to decreases in the US population rather than decreases in overall $PM_{2.5}$ exposure), but the number attributable to smoke $PM_{2.5}$ will increase. As fires will be a dominant source of $PM_{2.5}$ in the future (according to our RCP8.5 scenario simulations), smoke will also be a dominant source of $PM_{2.5}$ exposure and of the associated deaths. Due to the projected decrease in the US population in the SSP3 projection, the percentage of total deaths attributable to $PM_{2.5}$ exposure stays relatively consistent at ~4%.

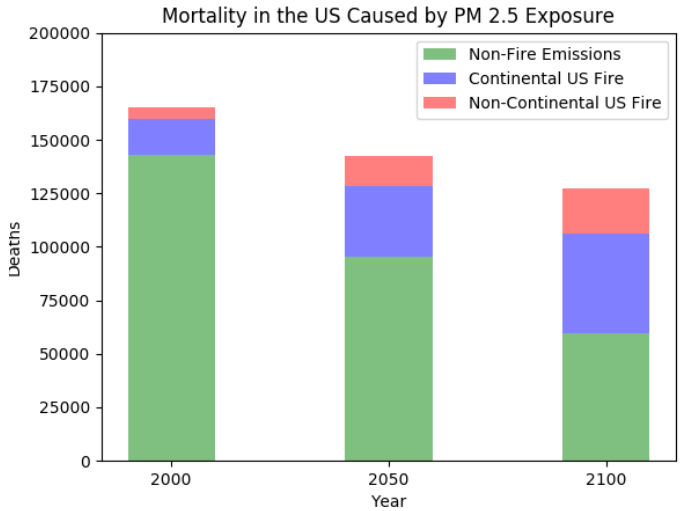

Figure 13. Premature mortality (deaths) per year over the US caused by $PM_{2.5}$ exposure, resulting from fires in continental US (blue) fires in Canada and Mexico (red) and non-fire sources, i.e., mostly anthropogenic emissions (green).

4.6 Potential to use WRF-Chem with CESM fire emissions

The original plan was to try to determine regional changes in PM due to changes in wildfire emissions using a regional model. Before doing so, we tried several different tests to determine the usefulness of this endeavor.

First, we wanted to determine if downscaling the meteorology would be necessary or if we could simply use a current year's meteorology with the future fire emissions. To test this, we did 2 one-year WRF-Chem simulations: (1) 2012 fire with 2012 emissions and (2) 2012 fire with 2014 meteorology. Figure 14 shows the percentage difference in smoke concentrations between the two simulations, suggesting that on average, our results could be off by ± 25 µg/m^3.

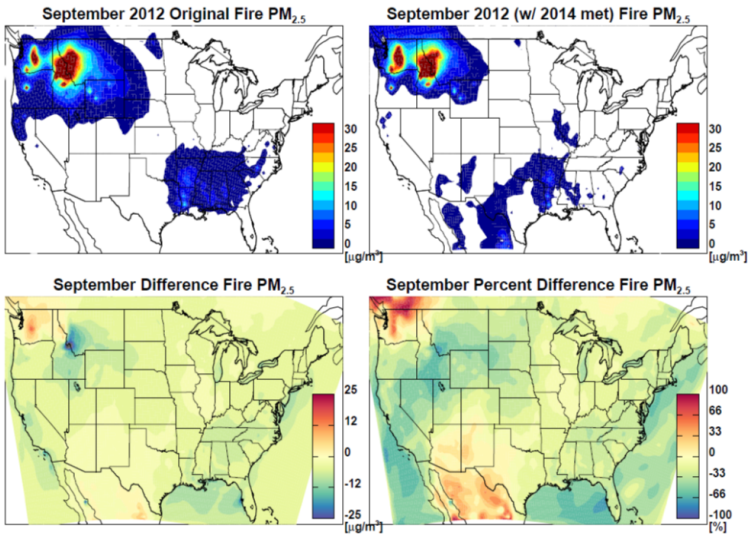

Figure 14. Comparison of the WRF-Chem simulations with 2012 emissions and meteorology (left), and 2012 emissions and 2014 meteorology (right). Shown are absolute (top) and relative (bottom) $PM_{2.5}$ changes.

Secondly, the emissions from CESM are on a 1.25° by 0.942° resolution. Our WRF-Chem simulations would be at a finer resolution. Therefore, we would need to choose how to regrid the emissions. We have two options: (1) redistribute the emissions to a smaller area or (2) keep the same area so that we are emitting smoke from a broad area into our domain. Option 1 requires that we make a decision about how to redistribute the emissions. In Pfister et al. [2014], they used a climatology of fire locations; however, this assumes that the fire climatology stays the same in the future, which is not supported by the CESM simulations. We decided to test the second option by running another WRF-Chem simulation in which we first created the fire emissions on the CESM grid and then regridding them to the WRF-Chem grid, keeping the same area. We found however, that this can lead to very different results in the model concentrations, with lower concentrations spread over a broader area instead of the expected higher concentrations over a smaller area.

Due to these findings, we determined that we likely would not gain much new information by running higher resolution simulations using the offline emissions from the global model. Downscaling the meteorology from the CESM runs could allow for the meteorology to better correspond to the emissions; however, choices would still have to be made for scaling the emissions to a finer resolution and to still correspond with the meteorological fields.

4.7 Science Delivery Activities

The science delivery activities consisted of multiple conference, seminars, and workshop presentations, an article published at the Fire Management Today magazine for the general

public, and the preparation of a set of manuscripts to be submitted in peer-reviewed journals. This project also served as a placement for an undergraduate student, Sarah Zelasky, through the REU summer program and provided the opportunity for a postdoc, Bonne Ford, to act as a mentor. Refer to Appendix B for the comprehensive list of science delivery outputs.

5. Conclusions and Implications for Management/Policy and Future Research

In this project, we investigated future wildfire activity and consequences on global air quality, with a specific focus on the United States. We focused on two major air pollutants, $PM_{2.5}$ and ozone, and employed the global Community Earth System Model (CESM) with the RCP climate, anthropogenic emissions and land use, and the SSP population projections. Within CESM, we used a complex-based fire parameterization [Li et al., 2012] to project future climate-driven and human-caused fire emissions.

We studied the effect of human intervention (i.e., fire ignition/suppression) on area burned and found that demographic changes may be a key factor controlling future fire emissions. Our results showed that area burned is very sensitive to population density, and future population growth may reinforce or counteract the impact of fire activity due to climate on a regional scale (e.g. tropical Africa). In future studies that project fire activity, researchers should take into account both climate and demographic changes.

We analyzed the changes in global area burned resulting from landscape, peat, deforestation, and agriculture fires from 1850 to 2100. Over North America, our simulations showed that future changes in area burned will be more noticeable after 2080 and decided to expand the scope of our project to the end of the century. Also, we found that agricultural fires will account for about 5-10% of the total area burned across the US. These findings are important for researchers as small, agricultural fires should be considered in future air quality studies. Also, they are of the interest of smoke managers, as better agricultural practices may need to be developed and new fire suppression strategies established to minimize fire pollution impacts.

In the US, our project showed that after 2050, fire pollution may be the dominant source of summertime PM_{25} in many regions. Fire pollution can even offset the benefits of reducing anthropogenic emissions in many states. This finding is key for air quality regulators as controlling anthropogenic emissions may not be enough to attain future air quality targets. Changes in the number of annual mortalities attributed to $PM_{2.5}$ as well as visibility degradation from $PM_{2.5}$ both showed similar effects to $PM_{2.5}$ changes, with increases in fire $PM_{2.5}$ offsetting benefits from anthropogenic $PM_{2.5}$ reductions.

Our high resolution simulations with the regional model WRF-Chem showed that meteorology is important for determining smoke impacts on local air quality. Smoke can be transported very far downwind, so it is necessary to have the meteorology corresponding to the fire emissions, even when looking at longer timescales (seasons to years). In addition, fire size and location is important to determining smoke impacts on local air quality. For the same total emissions, a fire that produces lower smoke emission fluxes over a broader area can have different air quality impacts compared to a fire that produces higher emission fluxes over a small area, even if the total emissions are the same.

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Appendix B. List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

1. Articles in peer-reviewed journals

   Val Martin, M, Pierce J. and Heald C. (2015), Studying the effects of changing climate on wildfires and impacts to the United States air quality, USDA Forest Service "Fire Management Today" Volume 74, 3.

   Val Martin, M, J. Pierce, C. Heald, F. Li and D. Lawrence, Global future air quality changes from fire pollution across the 21st Century, to be submitted to ACP

   Ford, B., Zelasky, S., Val Martin, M., Pierce, J., Predictions of future $PM_{2.5}$ and attributed mortalities and visibility degradation in the United States due to changes in wildfire smoke, to be submitted to ACP.

2. Technical reports N/A

3. Text books or book chapters N/A

4. Graduate thesis (masters or doctoral) N/A

5. Conference or symposium proceedings scientifically recognized and referenced N/A

6. Conference or symposium abstracts

Val Martin et al., Quantifying Future PM2.5 and Associated Health Effects Due to Changes in US Wildfires, American Geophysical Union Fall Meeting, New Orleans, Dec. 11-15, 2017; Abstract A31C-2196. (https://agu.confex.com/agu/fm17/meetingapp.cgi/Paper/253622)

Val Martin et al., Climate and human intervention effects on future fire activity and consequences for air pollution across the 21st century, American Geophysical Union Fall Meeting, San Francisco, Dec. 12-16, 2016; Abstract GC42C-07. (https://agu.confex.com/agu/fm16/meetingapp.cgi/Paper/141210)

Ford et al., How future fire activity will affect mid-century air quality over the United States, International Association of Wildland Fire, 2nd International Smoke Symposium, Long Beach, CA, Nov. 14-17, 2016. (http://www.iawfonline.org/ISS2%20Oral%20Presentation%20Abstracts.pdf)

7. Posters

M. Val Martin, J. Pierce, C. Heald, F. Li and D. Lawrence, Air Quality Changes from Fires in Developing Nations across the 21st Century, Atmospheric Chemistry in the Anthropocene Faraday Discussion, May 2-4, 2017. (http://pubs.rsc.org/en/content/articlepdf/2017/fd/c7fd90051a?page=search)

8. Workshop materials and outcome reports N/A

9. Field demonstration/tour summaries N/A

10. Website development N/A

11. Presentations/webinars/other outreach/science delivery materials.

Pierce, J.R., et al., Fire Emissions and Air Quality Impacts in Colorado and the West: Today and in the Future, Air Quality Control Commission Hosted Science Forum, Boulder, CO, April, 2017.

Pierce, J.R., et al., Single-model estimates of future fire activity, $PM_{2.5}$, and health impacts, EPA ORD visit to Colorado State University, Fort Collins, CO, August 2017.

Zelasky, S., et al., Quantifying Future Health Effects due to Changes in US Wildfire Frequency, CSU ESMEI REU Colloquium, Fort Collins, CO, July, 2017.

Val Martin, M., J. Pierce, C.L. Heald, D. Lawrence, F. Li, C. Wiedinmyer and F. Vitt, Climate-driven and human-caused fires within CESM, 21st Annual CESM Meeting, Breckenridge, CO, June 19, 2016.

Val Martin, M., J. Pierce, C.L. Heald, F. Li, C. Wiedinmyer and F. Vitt, Advances with the CESM fire module in coupled mode, 20th Annual CESM Meeting, Breckenridge, CO, June 16, 2015.

Val Martin, M. Earth observations and modeling: from air pollution transport to wildfires, Invited seminar at the Department of Geography, University of Sheffield, February 24, 2015.

Val Martin, M. Earth observations and modeling synergies: air pollution, wildfires, deposition and deposition, Invited Seminar at the School of Environmental Sciences, University of East Anglia, February 16, 2015.

Val Martin, M. Earth observations and modeling: from transport to deposition, Invited Seminar at the Department of Chemistry AWC Laboratory, University of York, January 20, 2015.

Appendix C: Metadata

We have followed the proposed Data Management Plan, and the data archived include the output from our simulations (about 86 Gb of data). We have prepared the metadata and files, and contacted the members of the US Forest Service Archive Team. As of the date of submission of the final report, we are awaiting their response to know how to best submit our files.

Appendix D. Additional Information

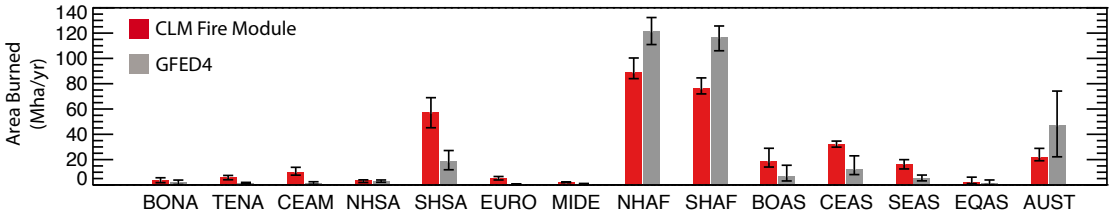

Figure S1. Regional annual area burned (Mha/yr) for GFEDv4 (grey) and CESM-CLM Fire Module (red). For a location of the fire regions see Figure S2.

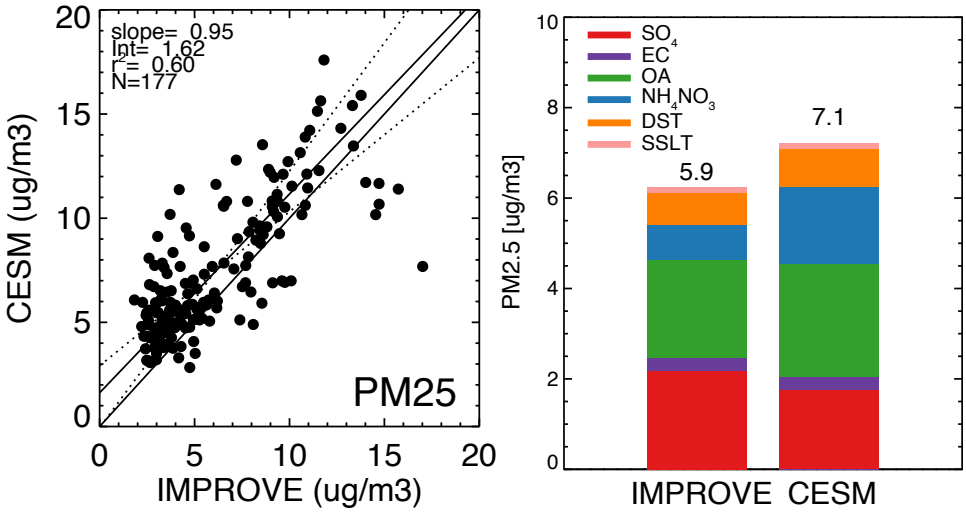

Figure S2. Simulated and observed present-day $PM_{2.5}$, with scatter plot of modeled and observed values at the individual IMPROVE sites (right), and comparison of main chemical species (left). Observations are long-term means from the IMPROVE (1998–2010) network.

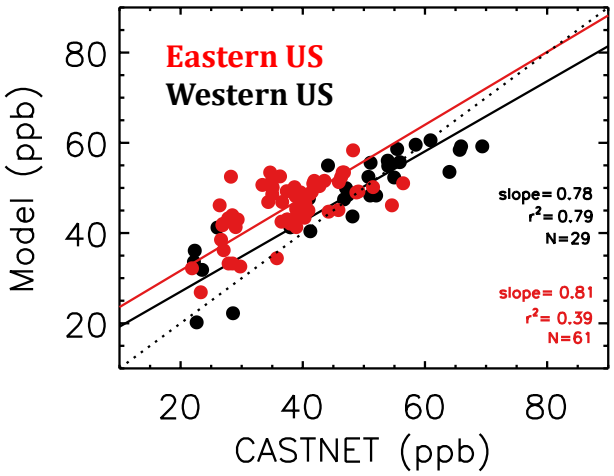

Figure S3. Simulated and observed present-day surface O_3 scatter plot. Observations are long-term means from the CASTNET (1995–2005) network.

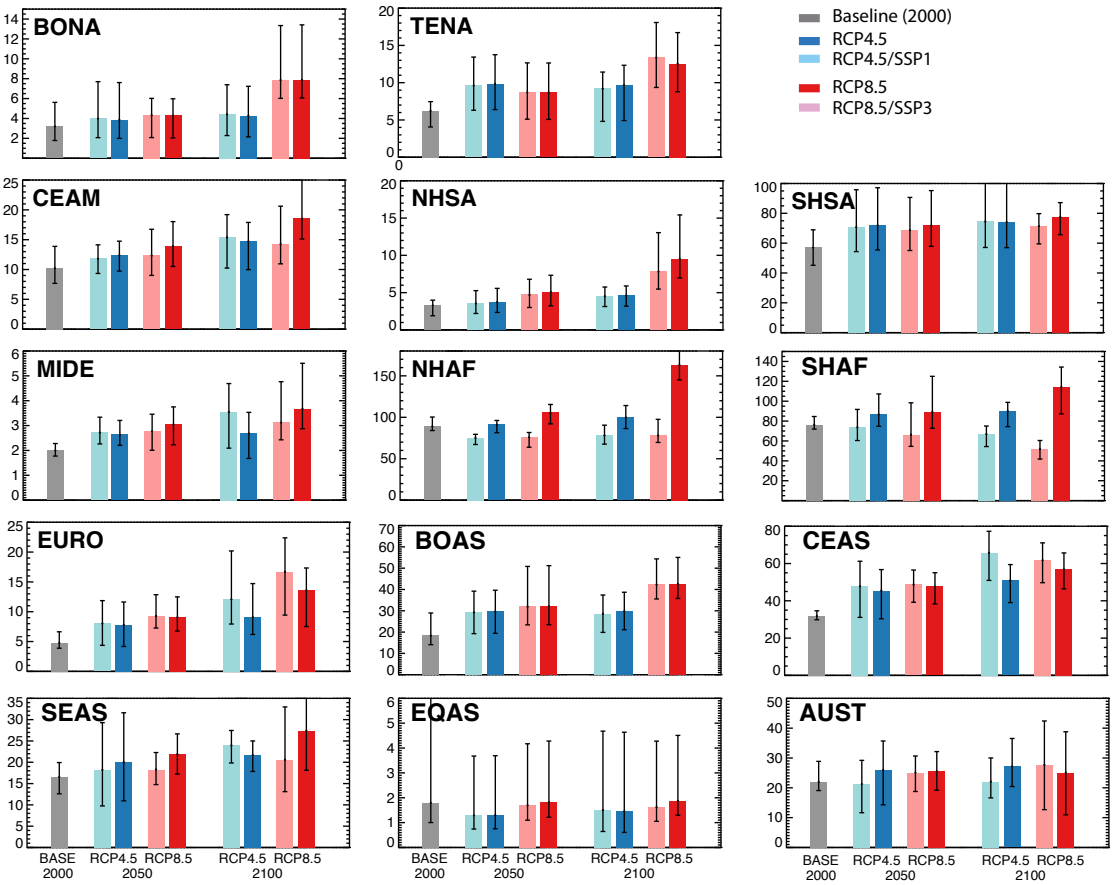

Figure S4. Fire area burned in each fire region for present-day, 2050 and 2100 as predicted by the RCP4.5 and RCP8.5 scenarios. Bars show decadal averages, with the minimum and maximum.

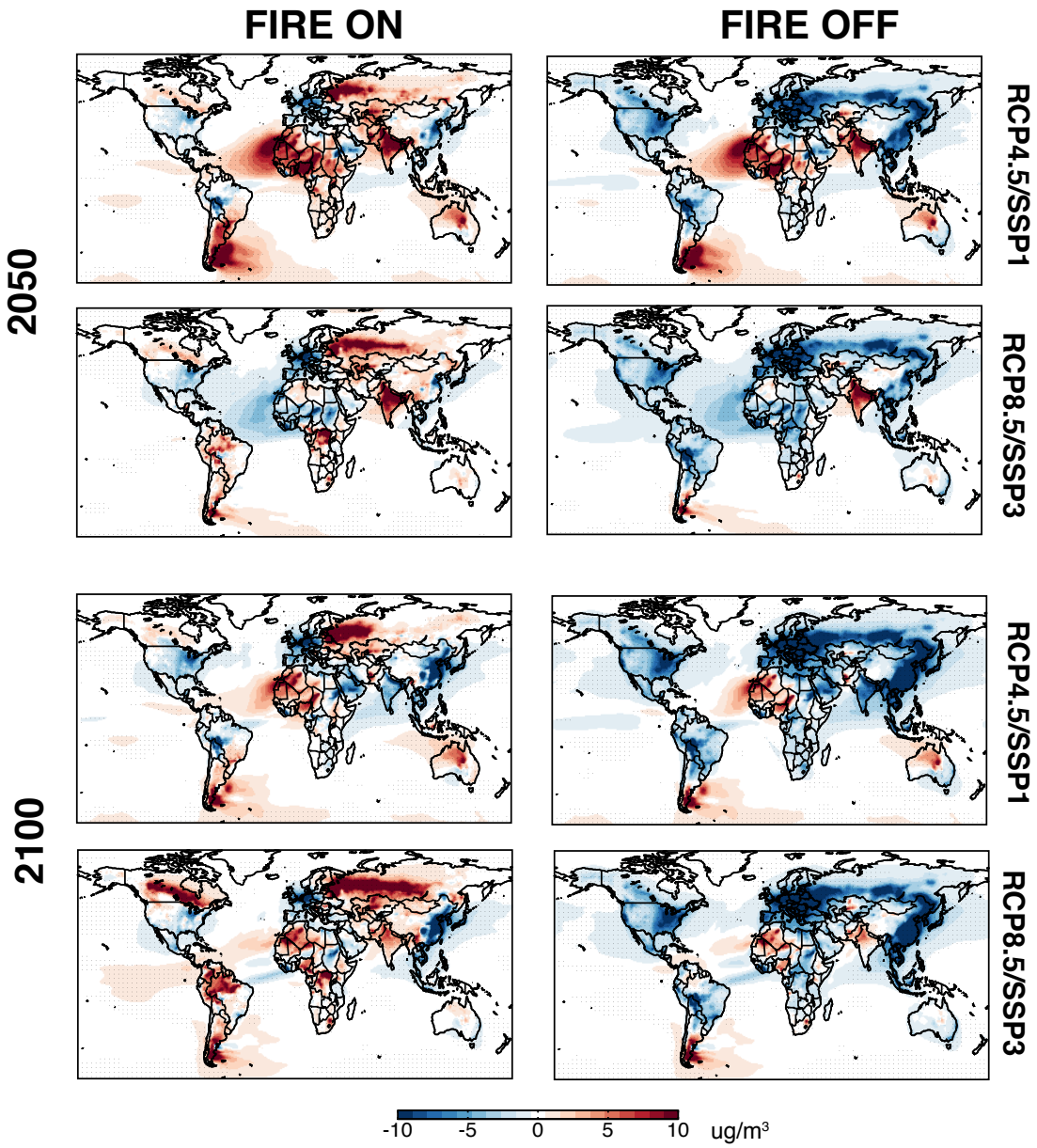

Figure S5. Projected simulated 2050–2000 and 2100-2000 changes in annual $PM_{2.5}$ as a result of the combination of climate, land use and emission changes for the RCP4.5/SSP1 and RCP8.5/SSP3 scenarios, with fire emissions on and off.

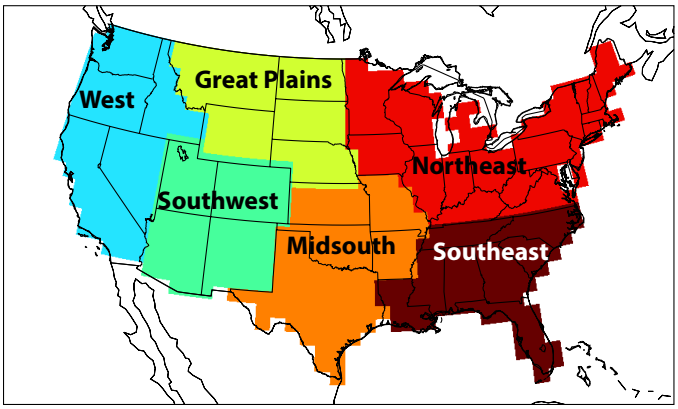

Figure S6. Map with the six climatic regions in the lower 48 states.