



# Projected increases in wildfires may challenge regulatory curtailment of PM<sub>2.5</sub> over the eastern US by 2050

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**Abstract.** Anthropogenic contribution to the overall fine particulate matter (PM<sub>2.5</sub>) concentrations has been declining sharply in North America. In contrast, a steep rise in wildfire-induced air pollution events with recent warming is evident in the region. Here, based on coupled fire–climate–ecosystem model simulations, summer-time wildfire-induced PM<sub>2.5</sub> concentrations are projected to nearly double in North America by the mid-21st century compared to the present. More strikingly, the projected enhancement in fire-induced PM<sub>2.5</sub> ( $\sim 1\text{--}2\ \mu\text{g m}^{-3}$ ) and its contribution ( $\sim 15\%\text{--}20\%$ ) to the total PM<sub>2.5</sub> are distinctively significant in the eastern US. This can be attributed to downwind transport of smoke from future enhancement of wildfires in North America to the eastern US and associated positive climatic feedback on PM<sub>2.5</sub>, i.e., perturbations in circulation, atmospheric stability, and precipitation. Therefore, the anticipated reductions in PM<sub>2.5</sub> from regulatory controls on anthropogenic emissions could be significantly compromised in the future in the densely populated eastern US.

## Highlights.

- Wildfire–PM<sub>2.5</sub> associations are studied based on unprecedented two-way coupled fire–climate–ecosystem model simulations.
- A steep rise in wildfire-induced air pollution events with recent warming is evident in the region.
- The transported smoke from enhanced wildfires in North America can severely affect air quality over the eastern US.

## 1 Introduction

Wildfires are widespread burning events in forests, shrublands, and grazing lands. In North America (mainly Canada and the US), particulate matter emissions from wildfires are a significant source of regional air pollution (Shi et al., 2019; McClure and Jaffe, 2018; van der Werf et al., 2010; Jaffe et al., 2008). Since the 1980s, the number of large wildfires and the length of the wildfire season have been increasing,

and the trends are projected to continue in the future over the western US, Alaska, and Canada (Kitzberger et al., 2017; Kirchmeier-Young et al., 2017; Abatzoglou and Williams, 2016; Partain et al., 2016; Jolly et al., 2015; Westerling et al., 2006; Gillett et al., 2004). Accordingly, particulate emissions from wildfires are also anticipated to increase in North America in the 21st century (Knorr et al., 2017; Liu et al., 2016; Val Martin et al., 2015). Human exposure to high concentrations of wildfire-emitted airborne particulate matter of diameter  $\leq 2.5\ \mu\text{m}$  (PM<sub>2.5</sub>) is known to have substantial adverse effects on pulmonary and cardiovascular functioning (Haik-erwal et al., 2021; Black et al., 2017), which contribute significantly to global and regional all-cause mortality (Zhang et al., 2020; Hong et al., 2019; Yang et al., 2019; Ford et al., 2018; Johnston et al., 2012). Therefore, a better understanding of the future changes in wildfire-induced PM<sub>2.5</sub> and its contribution to the total surface PM<sub>2.5</sub> is essential.

In the last 2 decades, ambient air quality in the US has substantially improved due to a decline in  $\text{PM}_{2.5}$  by  $\sim 40\%$  (US EPA, 2018). The decrease in  $\text{PM}_{2.5}$  is primarily due to curtailment of anthropogenic emissions resulting from US-based efforts to meet regulations such as the Clean Air Act (US EPA, 2009), Cross-State Air Pollution Rule, Regional Haze Rule, and the motor vehicles emissions standards. Consequently, air quality over the contiguous US (CONUS) and Canada has improved steadily such that it is predicted to achieve the targeted National Ambient Air Quality Standards in the future (Nolte et al., 2018). Under this promising scenario, the influence of wildfire-emissions on the total  $\text{PM}_{2.5}$  becomes even more crucial. Depending on the competition between climate-induced increase in wildfires and the regulatory control on anthropogenic emissions, future enhancement in wildfire-induced  $\text{PM}_{2.5}$  may compromise the reduction in anthropogenic  $\text{PM}_{2.5}$  concentrations in certain regions. In agreement, recent studies have highlighted the potential for future enhancement in wildfire-induced pollution to diminish the reducing trend in  $\text{PM}_{2.5}$ , primarily over the western US (O'Dell et al., 2019; Ford et al., 2018; Val Martin et al., 2015; Yue et al., 2013).

While the fractional wildfire-burned area and fire intensities are the greatest over the western US and Canadian regions within North America, anthropogenic emissions dominate the ambient  $\text{PM}_{2.5}$  concentration over the eastern US. The inherent geographical separation between the regions with large wildfire emissions and anthropogenic emissions leads to a pertinent question: will future enhancement in wildfires over the western US and Canada have significant effects on  $\text{PM}_{2.5}$  over the eastern US? Addressing this question is crucial because the declining trend in  $\text{PM}_{2.5}$  over the eastern US is the major contributor to the observed 40% decrease in  $\text{PM}_{2.5}$  over the US in the last 2 decades (US EPA, 2018). Eastward advection of wildfire smoke from Canada and the western US has been found to severely hamper the surface air quality of the central and eastern US under the influence of the prevailing westerlies during the summer months (Brey et al., 2018; Wu et al., 2018; Gunsch et al., 2018; Kaulfus et al., 2017; Dempsey, 2013). The transported wildfire smoke can influence the meteorology and climate via the radiative impact of carbonaceous emissions, changes in land albedo, and cloud system perturbations (Ward et al., 2012; Liu et al., 2014). These fire–weather interactions can have positive feedback on the locally emitted  $\text{PM}_{2.5}$  in the eastern US by surface cooling and boundary layer suppression (Guan et al., 2020). At the same time, fire-triggered ecosystem changes can induce negative feedback on  $\text{PM}_{2.5}$  by reducing the future wildfires over North America (Zou et al., 2020). Thus, two-way interactions between fires and climate that are important for predicting future changes in wildfire locations, intensities, and durations (Harris et al., 2016) as well as associated particulate emissions are essential. However, past studies have mostly employed simple statistical models based on statistical regressions of present-day fire-burned area on the

meteorological fields (Liu et al., 2016; Spracklen et al., 2009; Yue et al., 2013; Val Martin et al., 2015) and, more recently, one-way coupled modeling (Ford et al., 2018; O'Dell et al., 2019).

Here, based on new two-way coupled fire–climate–ecosystem simulations, we demonstrate the significance of wildfire-induced contributions to ambient  $\text{PM}_{2.5}$  over the eastern US due to enhanced wildfire smoke transportation and smoke-induced changes in weather in the eastern US. This enhancement in wildfire-induced  $\text{PM}_{2.5}$  may potentially challenge the targeted policy-driven reduction in  $\text{PM}_{2.5}$  in the eastern US. Next, our model setup, experiments, and methodology are explained in Sect. 2, followed by results and discussion in Sect. 3. The study is summarized in Sect. 4.

## 2 Materials and methods

### 2.1 RESFire–CESM model description

We employ the open-source Region-Specific ecosystem feedback Fire (RESFire) model coupled with the Community Land Model version 4.5 and the Community Atmosphere Model version 5 (CAM5) of the Community Earth System Model (CESM) version 1 (Zou et al., 2019; Neale et al., 2013) to perform two-way coupled simulations. RESFire provides state-of-the-art capabilities to simulate the complex fire–climate–ecosystem interactions globally for fires occurring over wildland, cropland, and peatland. Although wildfires dominate in the North American region, RESFire simulates both wildfires and prescribed fires. Moreover, this integrated setup includes climatic feedback from fire-induced aerosol direct and indirect radiative effects and associated weather changes. It also includes feedback from fire-induced vegetation distribution changes and associated biophysical processes such as evapotranspiration and surface albedo. Sofiev et al. (2012) described the fire plume rise parameterization. Other features in CLM4.5 and CAM5, such as the photosynthesis scheme (Sun et al., 2012), the MAM3 aerosol module (Liu et al., 2012), and the cloud macrophysics scheme (Park et al., 2014), allow for more comprehensive assessments of the climate effects of fires through their interactions with vegetation and clouds. Fire–ecosystem interactions are modeled by simulating fire-induced vegetation mortality and regrowth (and associated land cover change) in RESFire. This approach has been introduced in Zou et al. (2019), and the simulated ecological and climatic effects of wildfires have been evaluated in two sets of sensitivity experiments in Zou et al. (2020). Although fire–climate–ecosystem interactions are considered in this study, our focus is on the fire-induced changes in  $\text{PM}_{2.5}$  over Canada and the US, so the two vegetation-focused sensitivity experiments reported in Zou et al. (2020) are not included in this paper. Please refer to Zou et al. (2019) and Zou et al. (2020) for more details about the simulation of fire–ecosystem interactions.

## 2.2 Numerical experiment and methodology

We designed two sets of simulations for the present-day and future scenarios to quantify the impacts of fire–climate–ecosystem interactions (Table 1). The spatial resolution is  $0.9^\circ$  (lat)  $\times$   $1.25^\circ$  (long) with a time step of 30 min. In each set of simulations, we conducted a default all-emissions-included control run ( $X_{\text{ALL}}$ , where  $x = 2000$  or  $2050$  indicates the present day or future, respectively) and a sensitivity run with no wildfire emissions to the atmosphere ( $X_{\text{WEF}}$ , where  $X$  is the same as for the control runs). The ALL runs are designed to simulate fully interactive fire disturbances such as fire emissions with plume rise and fire-induced land cover changes in the present day (representative of the 2000s,  $2000_{\text{ALL}}$ ) and a moderate future emission scenario (representative of the 2050s,  $2050_{\text{ALL}}$ ) via the RCP4.5. The only difference between the ALL and WEF scenario is that wildfire emissions are absent in the WEF scenario. Specifically, in the WEF runs, the online-simulated fire emissions are not passed to the CAM5 atmosphere model so that the difference between the ALL and WEF runs can be used to isolate the atmospheric impacts of fire–climate interactions.

For the present-day experiments, we used the spun-up states from Zou et al. (2019) as initial conditions for both meteorological and chemical variables. Sea surface temperature (SST) for the present day was obtained from the Met Office Hadley Centre (HadISST). Present-day non-fire emissions from anthropogenic and other sources were based on ACCMIP (Lamarque et al., 2010) for the year 2000. We replaced the prescribed GFED2 fire emissions (van der Werf et al., 2006) in the default setting of CESM with the online-coupled fire emissions generated by the RESFire model. Zou et al. (2019) provided more details of the physics parameterizations and modeling experiment settings used in these simulations. Land use and land cover data for 2000 and 2050 from the Land-Use History A product (Hurt et al., 2006) are used to initialize the  $2000_{\text{ALL}}$  and  $2000_{\text{WEF}}$  as well as the  $2050_{\text{ALL}}$  and  $2050_{\text{WEF}}$  simulations, respectively. Following the above setup, the future scenario  $2050_{\text{ALL}}$  experiment accounts for both fuel load changes associated with the projected land use and land cover change (LULCC) in the 2050s and fire weather changes driven by the SST and sea ice forcing from a coupled CESM simulation following the greenhouse gas (GHG) forcing of the RCP4.5 scenario. The global-mean GHG mixing ratios in the CAM5 atmosphere model were fixed at year 2000 levels in all the present-day experiments, and they were replaced by those of the RCP4.5 scenario with the well-mixed assumption and monthly variations. However, the future population and socioeconomic conditions were identical to those of the present day, so there was no explicit impact of human-induced mitigation/enhancement effects on wildfires in the future projection in all the future experiments. Future human impacts were considered implicitly in LULCC-induced fuel load changes in the RCP4.5 scenario.

The net projected changes by the 2050s in emissions, meteorology, and air quality during summer months (JJA: June, July, August) are estimated by comparing decadal-mean values simulated by  $2000_{\text{ALL}}$  with  $2050_{\text{ALL}}$ . Wildfire-induced enhancement in  $\text{PM}_{2.5}$  concentration in the present day and mid-21st century is estimated by comparing  $2000_{\text{ALL}}$  with  $2000_{\text{WEF}}$  and  $2050_{\text{ALL}}$  with  $2050_{\text{WEF}}$ , respectively. Further, the projected increase in wildfire-induced  $\text{PM}_{2.5}$  in the future is calculated by comparing the simulated wildfire effect of the 2050s ( $2050_{\text{ALL}} - 2050_{\text{WEF}}$ ) with that of the 2000s ( $2000_{\text{ALL}} - 2000_{\text{WEF}}$ ). With large spatiotemporal variability, the projected changes in transported fire-emissions from the western US and Canada to the eastern US by the 2050s and the corresponding impacts are summarized using probability distribution functions. The latter provide information for not only the mean but also variability and extreme values to quantify the simulated changes for the three subregions.

## 3 Results and discussion

### 3.1 Model evaluation

Zou et al. (2019) performed comprehensive evaluation of the RESFire-simulated wildfire-burned area distribution, associated carbon emissions, and terrestrial carbon balance to demonstrate reasonable model skill. Zou et al. (2020) compare global fire simulations by RESFire–CESM with modeling results reported in the literature to show better agreement with the GFED4.1s benchmark data and predict more prominent changes in the future than those predicted by Kloster et al. (2010, 2012). These differences might come from differences in the climate sensitivities of the fire models and scenarios and other input data used to make future projections.

Here, we evaluate the simulated surface  $\text{PM}_{2.5}$  against satellite estimates (Fig. 1) over North America. The  $\text{PM}_{2.5}$  concentration is calculated as the sum of sulfate, nitrate, fine sea salt (first two size bins), fine dust (first size bin), black carbon (BC), and organic aerosol (OC) at the surface level of the model. OC is the sum of primary organic matter (POM) and secondary organic aerosol (SOA), and SOA is the sum of secondary species formed from toluene, monoterpenes, isoprene, benzene, and xylene. Figure 1 compares the observed and simulated mean annual  $\text{PM}_{2.5}$  averaged over 2001–2010. The 10-year-average satellite AOD-derived annual-mean surface  $\text{PM}_{2.5}$  concentrations (Van Donkelaar et al., 2018) are regridded to the model grid (Fig. 1a) and then compared with the RESFire simulations in the  $2000_{\text{ALL}}$  present-day run (Fig. 1b). The spatial distribution of annual surface  $\text{PM}_{2.5}$  is reasonably well simulated but also has some biases. To quantify the biases, we also estimated the correlation coefficient as well as normalized mean biases (NMBs) of the simulated values compared against the satellite-retrieved values over two subregions. Quantitatively, the NMB values over the western US (WUS) and eastern US (EUS) are 18 % and 7 %, respectively (Fig. 1c–d). In addition, the spatial

**Table 1.** Summary of the sensitivity simulations performed.

Scenario	Present day		Future	
Experiment name	2000 <sub>ALL</sub>	2000 <sub>WEF</sub>	2050 <sub>ALL</sub>	2050 <sub>WEF</sub>
Simulation years	2001–2010	2001–2010	2051–2060	2051–2060
Atmosphere	CAM5	CAM5	CAM5	CAM5
Land	CLM4.5	CLM4.5	CLM4.5	CLM4.5
Ocean	Climatology	Climatology	RCP4.5	RCP4.5
Sea ice	Climatology	Climatology	RCP4.5	RCP4.5
Non-fire emissions	ACCMIP	ACCMIP	RCP4.5	RCP4.5
Fire emission	Online fire aerosols with plume rise	–	Online fire aerosols with plume rise	–
Land cover	Fire disturbances under present-day conditions	Fire disturbances under present-day conditions	Fire disturbances under RCP4.5 conditions	Fire disturbances under RCP4.5 conditions

variability in the 2001–2010 averaged annual AOD distribution (Supplement Fig. S1) is also well represented in our simulation, although the model underestimates high AOD values. Similar spatial variability and biases in AOD and PM<sub>2.5</sub> were also found when a comparison was performed for only summer months (JJA). The simulated PM<sub>2.5</sub> has also been evaluated against the ground-based Interagency Monitoring of Protected Visual Environments (IMPROVE) data, showing similar spatial pattern and biases (10%–25%) (Supplement Fig. S2). The biases are smaller over the eastern US and southwestern US region. The simulated PM<sub>2.5</sub> values over California match quite well with the observed annual-mean values. However, the biases over the northwestern US region are ~30%–40%, a portion of which could be attributed to possible biases in the model's meteorology in the northwestern US region. Nonetheless, both satellite and in situ evaluation indicates that our simulation biases are largely within the uncertainty range among the various satellite- and ground-based datasets, which have normalized mean biases ranging from –3.3%–33.3% when benchmarked against the ground-based IMPROVE data over the contiguous US (Diao et al., 2019; Val Martin et al., 2015).

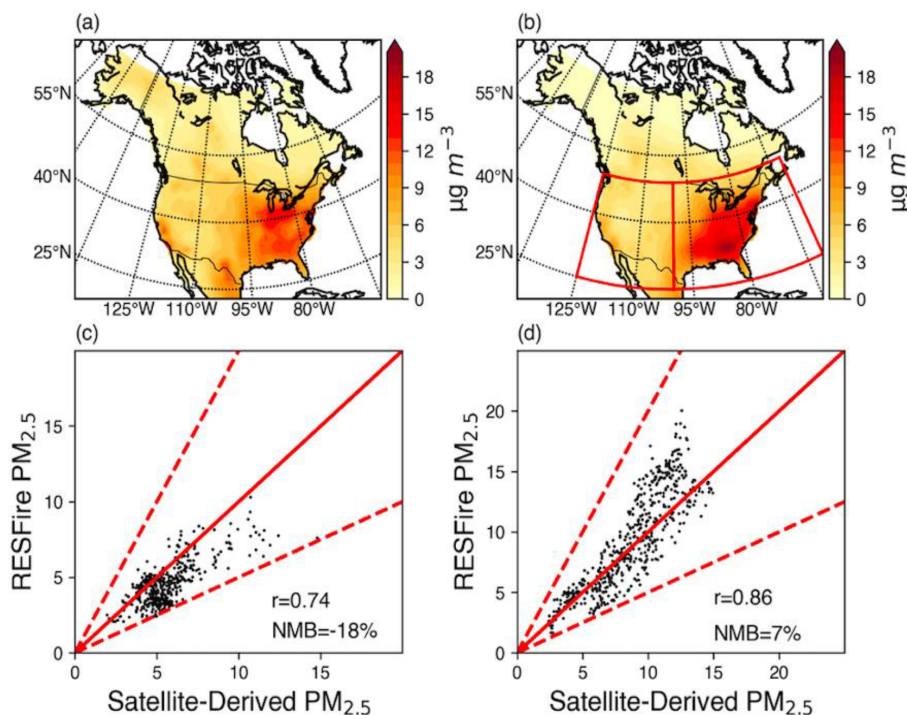
Discrepancies between the simulated and observed PM<sub>2.5</sub> values may be attributed to several potential reasons. First, the satellite-derived data have a non-zero lower bound of PM<sub>2.5</sub> concentrations, so the ambient background concentrations for relatively cleaner regions such as the western US may be overestimated (Fig. 1c), also the sampling frequencies between these datasets are different. Second, year-2000-based constant non-fire emissions were used in the RES-Fire simulation, which may result in overestimation of the PM<sub>2.5</sub> concentrations from non-fire sources during 2001–2010 when anthropogenic emissions and PM<sub>2.5</sub> concentrations continue to decrease (US EPA, 2018). This overestimation is prominent in regions dominated by non-fire sources

such as the southeastern US. Third, large uncertainties in fuel consumption and emission factors preclude an accurate estimation of the primary fire emissions in the model, especially for the eastern US, where large fractions of low-intensity prescribed fires consume only under-canopy fuels such as litter and duff layers. The fire model may fail to capture the subtle distinctions between low-intensity prescribed fires and forest fires, so more fuels are consumed and result in higher emissions. Lastly, comparison of a coarsely resolved simulation against in situ observations also contributes to uncertainty. Differences in the degree to which fire–climate interactions and other physical processes and feedbacks are represented by the models can explain the slight differences in estimating the present-day mean wildfire-induced change in PM<sub>2.5</sub> over local and downwind regions between our simulations and previous studies. Nonetheless, reasonable simulation of the spatial distribution of wildfire-burned area, AOD, and near-surface particulate concentration (mean bias of ~10%–20%) instills confidence about the fidelity of our model setup in particulate pollution simulation, which is the focus of this study.

### 3.2 Fire-induced changes in burned area and PM<sub>2.5</sub>

The decadal-mean annual fire-burned area simulated for the present day shows widespread wildfires over all of North America (Fig. 2a). Specifically, Canada and the forested areas of the northwestern (>36° N latitude) and southeastern (<36° N latitude) US are most intensely affected by wildfires in the present day. By the mid-21st century, a striking increase of a factor of 2–5 in fire-burned area is projected over Canada, Alaska, the Pacific Northwest, and portions of the western US by the 2050s (Fig. 2b). A distinct positive shift in the probability density function (PDF) of annual fire-burned area is evident in the future, with the decadal-mean difference





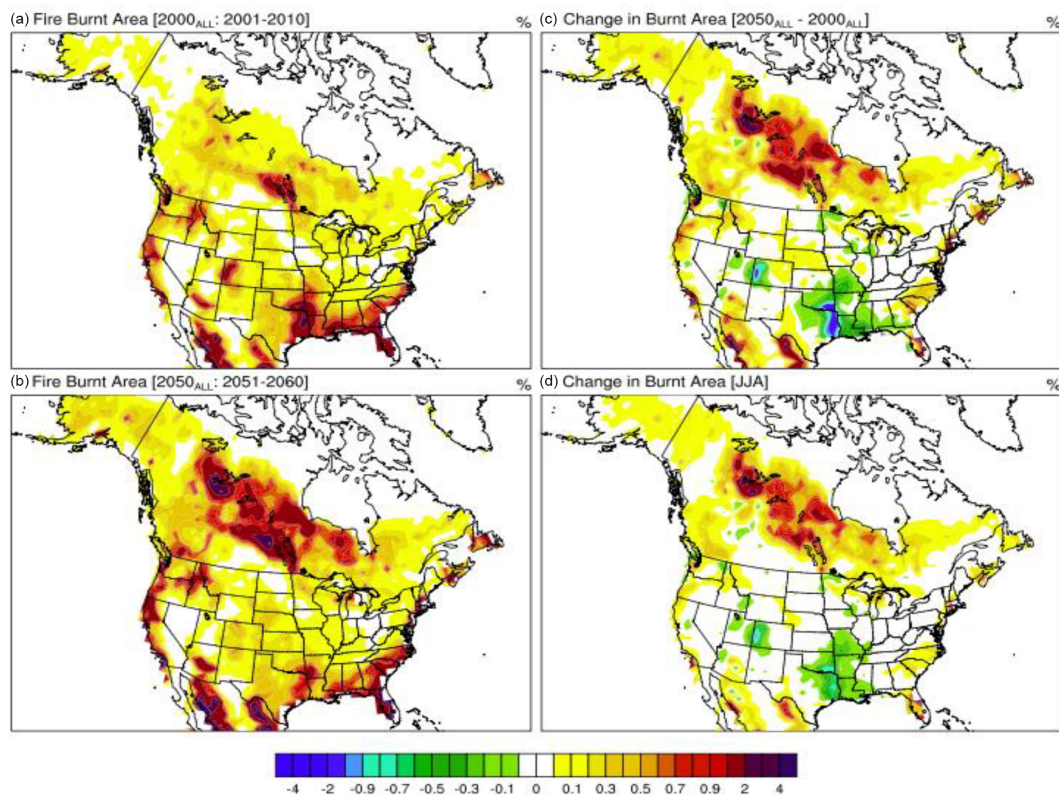
**Figure 1.** Comparison of the 10-year-averaged (2001–2010) annual-mean surface  $\text{PM}_{2.5}$  concentration between observations and RESFire simulations. **(a)** Satellite-derived surface  $\text{PM}_{2.5}$  concentrations (with dust and sea salt removed) estimated by van Donkelaar et al. (2018) (available at <https://sedac.ciesin.columbia.edu/data/set/sdei-global-annual-gwr-pm2-5-modis-misr-seawifs-aod>, last access: 5 November 2021). **(b)** The 2000<sub>ALL</sub> simulated surface  $\text{PM}_{2.5}$  concentrations (with dust and sea salt removed) averaged over 2001–2010; the red boxes denote the two subregions (EUS and WUS) shown in Fig. 2 in the main text. **(c)** Comparison of simulated and satellite-based gridded surface  $\text{PM}_{2.5}$  concentrations in the WUS subregion; the number of samples is equal to the number of land grids ( $\sim 450$ ). **(d)** Same as **(c)** but in the EUS subregion. The number of samples is equal to the number of land grids ( $\sim 375$ ). The solid and dashed red lines denote the 1 : 1 ratio line and  $\pm 100\%$  biases, respectively. The correlation coefficients and NMB values are shown at the lower-right corner of each subplot.

statistically significant at the 99 % confidence level (Zou et al., 2020). A small and statistically insignificant change in interannual variability ( $\sim 0.4 \text{ Mha yr}^{-1}$ ) of fire-burned areas is also simulated between the present and future. Specifically, our model predicts more than a doubling of burned area in boreal regions of Canada in the future, in line with a previous projection for Canada (Wotton et al., 2017). Future enhancement in fire-burned area is  $\sim 20\%$ – $50\%$  in most fire grids over the western coast of the US, which is higher than that over the eastern US (Fig. 2a and c). The increase over the western US is closer to the lower bound of that derived from statistical model ensemble projections for the western US in the mid-21st century (Yue et al., 2013). The statistics-based projections of future burned area over North America were likely too high because fire-induced land cover change, fuel load reduction, and other factors could induce a negative fire feedback, which was not considered in previous fire projection studies (Zou et al., 2020).

Annual fire-burned area in the southeastern US shows a decline in the future (Fig. 2c), as precipitation is projected to increase in that region (discussed later). Note that all future

fire changes between 2050<sub>ALL</sub> and 2000<sub>ALL</sub> are primarily associated with climate warming in response to the increase in greenhouse gas (GHG) concentrations in the RCP4.5 scenario. No direct impacts of population and socioeconomic changes on wildfires are included in our simulations, although these factors contribute to changes in GHG emissions (via the Representative Concentration Pathway – RCP – scenario) that influence the climate simulated in 2000<sub>ALL</sub> and 2050<sub>ALL</sub>. As about 80 % of the projected fire changes in the future are restricted to the summer season (JJA) (Fig. 2d), we focus on analysis of the summer-mean wildfire-induced  $\text{PM}_{2.5}$  and its projected future changes over North America.

The simulated 10-year-averaged summer-mean wildfire-induced  $\text{PM}_{2.5}$  values in 2000<sub>ALL</sub> are more than  $0.5 \mu\text{g m}^{-3}$  over a large part of North America in the present day, with noticeably larger values ( $> 1 \mu\text{g m}^{-3}$ ) in Canada and the northwestern, central, and southeastern US (Fig. 3a). Interestingly, the spatial distribution of wildfire-induced  $\text{PM}_{2.5} > 1 \mu\text{g m}^{-3}$  resembles an inverted horseshoe shape. The inverted horseshoe-shaped spatial distribution is also consistent with the wildfire smoke climatology derived from



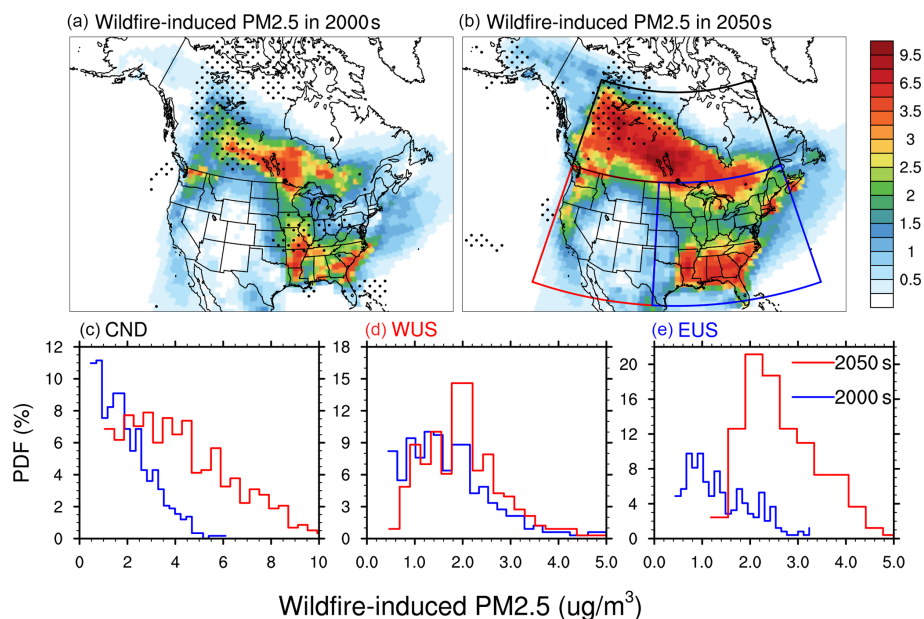
**Figure 2.** Spatial distribution of fire-burned area. (a–d) Spatial distribution of simulated decadal-mean annual burned area (as a percentage) over North America for the present day (a) and the mid-21st century (b) and the net change between the 2050s and the 2000s (c). (d) Same as (c) but for wildfire-burned area during summer only (JJA). The color bar illustrates the grid fraction of area burned.

the satellite-guided operational smoke product of the Hazard Mapping System (HMS) during 2005–2015 (Brey et al., 2018; Kaulfus et al., 2017). By the mid-21st century, the spatial extent of the horseshoe shape for areas with wildfire-induced  $\text{PM}_{2.5}$  enhancement  $> 1 \mu\text{g m}^{-3}$  expands significantly to span most regions of North America, with the most pronounced enhancement occurring over Canada (Fig. 3b). The PDFs of the spatial distribution for the three regions can be seen in Fig. 3c–e. Specifically, wildfire-induced  $\text{PM}_{2.5}$  in the 2000s over Canada and the WUS and EUS during summer is  $\sim 1\text{--}3$ ,  $1\text{--}3$ , and  $0.6\text{--}1.2 \mu\text{g m}^{-3}$ , respectively. Maximum values within the WUS region are found over the Pacific Northwest, with most areas having wildfire-induced  $\text{PM}_{2.5}$  values of  $\sim 2\text{--}3 \mu\text{g m}^{-3}$ . Similarly, the southern states have relatively high wildfire-induced  $\text{PM}_{2.5}$  concentrations of  $\sim 2\text{--}4 \mu\text{g m}^{-3}$  within the EUS in the present-day simulation.

Compared to the 2000s, the wildfire-induced JJA-averaged  $\text{PM}_{2.5}$  values are almost doubled to  $\sim 3\text{--}6 \mu\text{g m}^{-3}$  over Canada in the 2050s (Fig. 3b and c). Consistently, the values of wildfire-induced  $\text{PM}_{2.5}$  over the WUS (mainly coastal) also doubled in the 2050s compared to the 2000s, with modal values of  $\sim 2\text{--}2.5 \mu\text{g m}^{-3}$  (Fig. 3d). Most interestingly, the enhancement in wildfire-induced summer-mean  $\text{PM}_{2.5}$  over

the northern EUS is also significant by the 2050s (Fig. 3b). Largely, the summer-mean wildfire-induced  $\text{PM}_{2.5}$  concentration over the EUS increases from  $\sim 0.8$  to  $\sim 2 \mu\text{g m}^{-3}$  in the mid-century to values of  $1.2\text{--}3.0 \mu\text{g m}^{-3}$  (Fig. 3e). The summer-mean wildfire-induced  $\text{PM}_{2.5}$  is thus projected to double in North America by the 2050s compared to the 2000s, with a substantial coverage over the EUS. An important finding from these PDFs appears to be that there are fewer grids with  $< 1 \mu\text{g m}^{-3}$  wildfire-induced  $\text{PM}_{2.5}$  or, alternatively, that more regions are being influenced by  $\text{PM}_{2.5}$ , and many areas that were already seeing wildfire impacts are seeing enhanced impacts. Such enhancement is found not only at the surface but also in an elevated atmospheric layer over the EUS between 900 and 700 hPa. This is nonintuitive given the fact that the increase in fire-burned area by mid-century over the EUS is not substantial.

As anthropogenic- and wildfire-induced  $\text{PM}_{2.5}$  concentrations may change differently with time across North America, next, we investigate the relative contribution of wildfire-induced  $\text{PM}_{2.5}$  to the total  $\text{PM}_{2.5}$  in the future. Prominent enhancement of the wildfire contribution is apparent in the entire domain by the 2050s (Fig. 4a–b). Largely, during the 2000s, the simulated fractional contribution of wildfires to  $\text{PM}_{2.5}$  is  $\sim 15\%\text{--}50\%$  in Canada (Fig. 4a). Specifically, a



**Figure 3.** Spatial distribution of  $\text{PM}_{2.5}$  concentrations. Spatial distribution of decadal-mean wildfire-induced enhancement in summer (JJA)  $\text{PM}_{2.5}$  concentration over North America for the present day (2000<sub>ALL</sub>–2000<sub>WEF</sub>) (a) and the future (2050<sub>ALL</sub>–2050<sub>WEF</sub>) (b). The grids with statistical significance of 90 % are identified by black dots. (c–e) Probability density functions (PDFs) of wildfire contribution within the three regions shown in Fig. 2b for Canada (CND: black box) (c), the WUS (red box) (d), and the EUS (blue box) (e), respectively, for the 2000s (blue) and the 2050s (red). Only grids over land in North America are used to generate the PDFs. The y axis indicates the probability of occurrence of different  $\text{PM}_{2.5}$  values shown on the x axis. The color bar illustrates  $\text{PM}_{2.5}$  in micrograms per cubic meter.

bi-modal distribution is simulated over Canada with modal values around 18 % and 30 % (Fig. 4c). Over the WUS, the present-day simulated percentage contributions of wildfire-induced values are 5 %–25 % (Fig. 4a), with modal values between 10 %–20 % (Fig. 4d). Note that many areas located in the Pacific Northwest have higher values of  $\sim 30\%$ – $40\%$  (Fig. 4a). At the same time, the fractional contribution by wildfire-induced  $\text{PM}_{2.5}$  is  $\sim 5\%$ – $10\%$  in most areas of the EUS in the present day (Fig. 4f). Nevertheless, some areas in the central US also have higher values of  $\sim 10\%$ – $25\%$  (Fig. 4a).

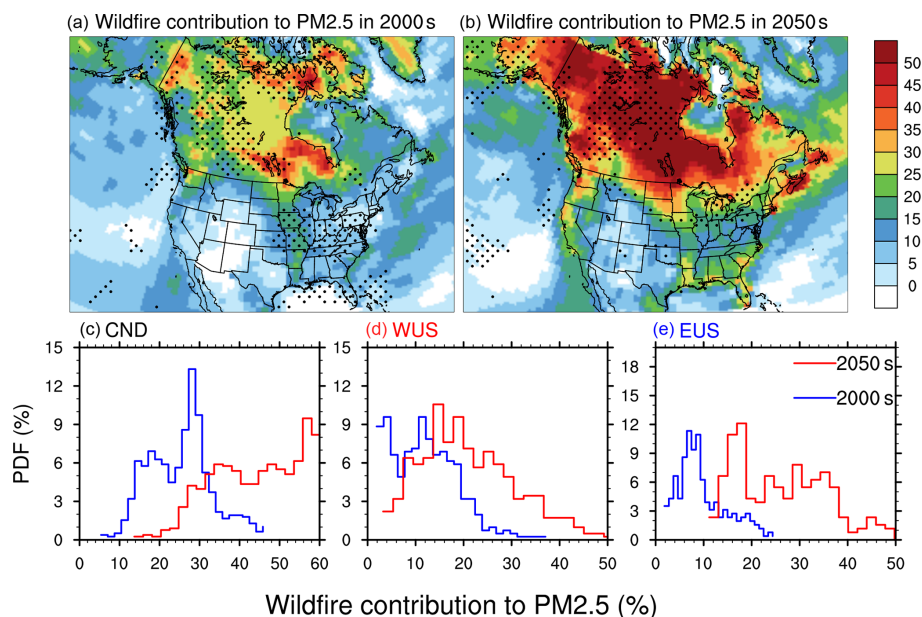
The wildfire contributions in the 2050s show a clear shift towards higher values in all subregions compared to the 2000s (Fig. 4b). Over Canada, the values shifted from 15 %–30 % in the 2000s to  $\sim 30\%$ – $60\%$  in the 2050s; a nearly 2-fold increase in the fractional contribution of wildfire emissions to the total  $\text{PM}_{2.5}$  concentration is simulated (Fig. 4b and corresponding PDF in Fig. 4c). Similarly, the contribution values increased to  $\sim 10\%$ – $35\%$  in the 2050s, compared to 10 %–20 % in the 2000s over the WUS (Fig. 4b), thereby featuring a broadening of the bi-modal distribution of wildfire contribution (Fig. 4d). The shift in the percentage contribution is most prominent for the higher values, corresponding to some areas located in the Pacific Northwest and on the west coast of the US (Fig. 4b). Consistent with Fig. 3b, the shift in the contribution values over the EUS is also very distinct, revealing an increase in the mode values from 6 %–

10 % in the 2000s to  $\sim 16\%$ – $20\%$  by the 2050s (Fig. 4b and e). Thus, our results underscore a large increase in not only absolute values but also the contribution of wildfire emissions over the EUS in the future.

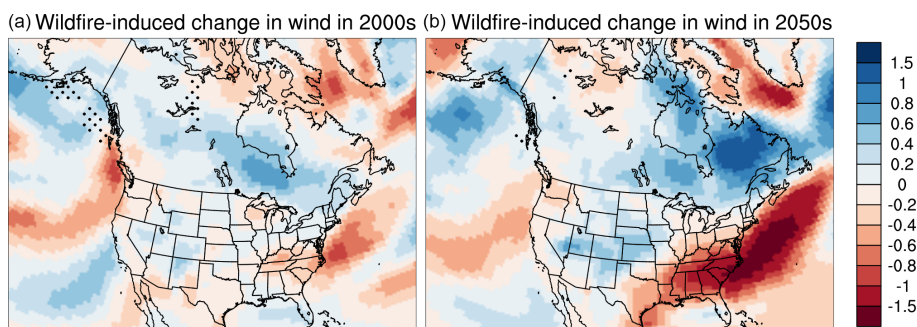
### 3.3 Mechanistic understanding of the underlying processes

The larger enhancement in the relative contribution of wildfire emissions to the total surface  $\text{PM}_{2.5}$  in the EUS in the 2050s can be explained by three mechanisms. First, due to the increase in Canadian and western US wildfires, downwind transport of wildfire smoke plumes to the EUS will be enhanced by the 2050s. This long-range transport to the atmospheric column of the EUS can happen within a few days of the fire occurrence (Supplement Fig. S3a and b). Using HMS-detected smoke plumes, recent studies identified a strong positive association between the transported smoke plumes in the atmospheric column and collocated surface  $\text{PM}_{2.5}$  enhancement in the EUS (Brey et al., 2018; Wu et al., 2018; Gunsch et al., 2018; Kaulfus et al., 2017; Larsen et al., 2017; Dempsey, 2013). HMS is an operational smoke detection product over North.





**Figure 4.** Spatial distribution and probability density function of the percentage contribution of wildfire emissions. **(a–b)** Spatial distribution of the percentage contribution of wildfire emissions to decadal-averaged summer (JJA) mean  $\text{PM}_{2.5}$  concentrations over North America during the present day **(a)** and the future **(b)**. The percentage contribution of wildfire-induced  $\text{PM}_{2.5}$  to the total  $\text{PM}_{2.5}$  concentrations is calculated as  $(2000_{\text{ALL}} - 2000_{\text{WEF}}) / 2000_{\text{ALL}}$  and  $(2050_{\text{ALL}} - 2050_{\text{WEF}}) / 2050_{\text{ALL}}$  for the present and future, respectively. The grids with statistical significance of 90 % are identified by black dots. **(c–e)** Probability density functions (PDFs) of the percentage of wildfire contribution within the three regions shown in Fig. 2d for Canada (CND: black box) **(c)**, the WUS (red box) **(d)**, and the EUS (blue box) **(e)**, respectively, for the 2000s (blue) and the 2050s (red). Only grids over land in North America are used to generate the PDFs. The y axis indicates the probability of occurrence of different  $\text{PM}_{2.5}$  values shown on the x axis.



**Figure 5.** Spatial distribution of decadal-mean summer (JJA) wildfire-induced future changes  $((2050_{\text{ALL}} - 2050_{\text{WEF}}) - (2000_{\text{ALL}} - 2000_{\text{WEF}}))$ . **(a)** Wind speed below 850 hPa for  $2050_{\text{ALL}} - 2000_{\text{ALL}}$ , **(b)** wind speed below 850 hPa for  $2050_{\text{WEF}} - 2000_{\text{WEF}}$ . The unit is meters per second. The grids with statistical significance of 90 % are identified by black dots.

America developed by the National Oceanic and Atmospheric Administration (NOAA) and operated by the National Environmental Satellite, Data, and Information Service (NESDIS), available at <http://satepsanone.nesdis.noaa.gov/FIRE/fire.html> (last access: 20 November 2022). Specifically, these studies found that the smoke plumes transported from Canada are located at an altitude of  $\sim 1\text{--}3$  km over the EUS (Colarco et al., 2004; Wu et al., 2018). Due to mixing by the daytime boundary layer and deposition, the smoke plumes enhance the surface  $\text{PM}_{2.5}$  concentration over

the EUS (Wu et al., 2018; Colarco et al., 2004; Rogers et al., 2020; Dreessen et al., 2015). Hence HMS smoky days may be a useful proxy for wildfire-induced surface  $\text{PM}_{2.5}$  over North America. In agreement, Brey et al. (2018) showed that the HMS-based smoke plumes observed over the EUS are significantly aged, suggestive of their long-range-transport origin. Consistent with the observed temporal change in HMS pattern, Xue et al. (2021) estimated using the mid-visible Multi-Angle Implementation of Atmospheric Correction (MAIAC) satellite-derived aerosol optical depth



(AOD) that Canadian and western US fires have caused an increase in the daily  $\text{PM}_{2.5}$  over Montana, North Dakota, South Dakota, and Minnesota by 18.3, 12.8, 10.4, and  $10.1 \mu\text{g m}^{-3}$ , respectively, between August 2011 (a low-fire month) and August 2018 (a high-fire month). In summary, the visually apparent satellite-based signatures of wildfire smoke across Canada and the EUS provide necessary, though not sufficient, support for the influence of Canadian smoke plumes on EUS air quality. Although, the change in burned area over the northeastern EUS is negligible compared to the western US and Canadian regions, there are some enhancements seen over the east coast of the US, which can also contribute to enhanced fire emissions.

In the future, the wildfire-induced change in speed of the westerly jet flows over Canada wildfire regions is increased (Fig. 5a–b). It indicates that the westerly-induced transported wildfire emissions from Canada boreal forests to the eastern half of North America and the EUS will be enhanced in the future compared to that in the present era. On the one hand, the wildfire-induced changes in wind speed over the EUS are reduced in the future, which implies that the local emissions over the EUS are less dispersed. Simultaneously, this will also cause the transporting smoke plumes to slow down and be subjected to relatively more boundary layer mixing over the EUS and dry deposition/settling enhancements, thereby contributing to the enhanced  $\text{PM}_{2.5}$  values at the surface. The westerly winds over the western US below  $40^\circ\text{N}$  are also strengthened in the future (Fig. 5a–b) compared to the present day, which indicates more advection flux wildfire emissions to the EUS. Thus, the net effect is more removal of wildfire-emitted  $\text{PM}_{2.5}$  from the WUS and more influx of wildfire-emitted  $\text{PM}_{2.5}$  in the EUS.

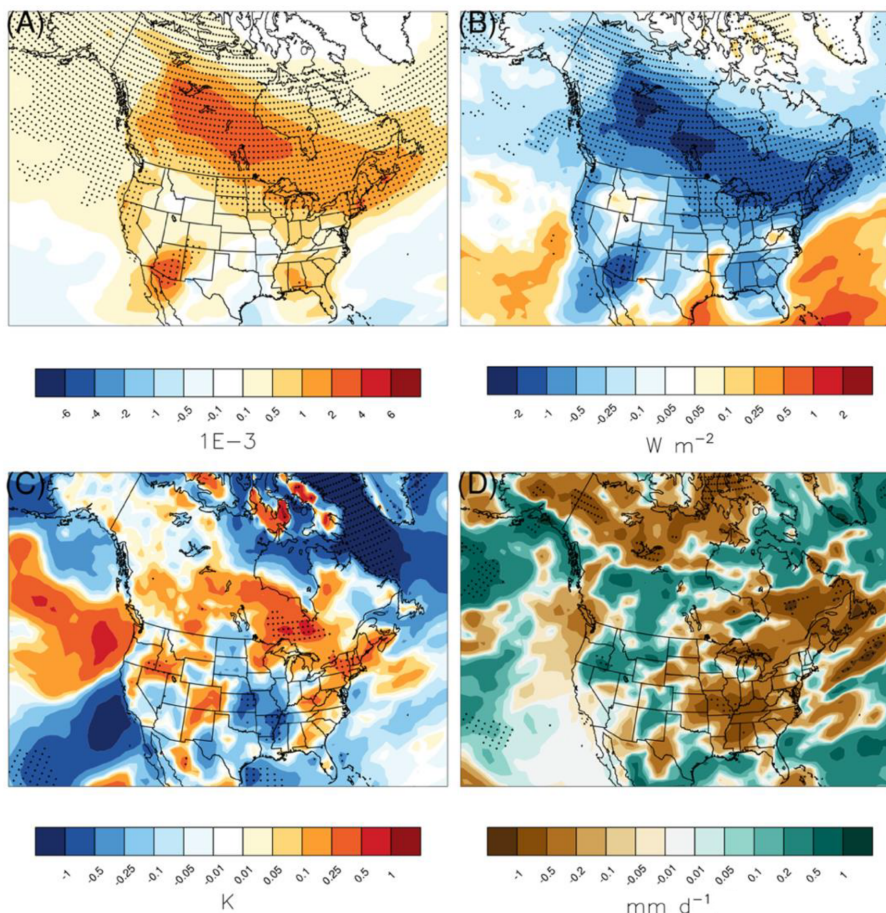
Along with these dynamical changes, other climatic feedbacks simulated can also contribute to enhancement of EUS pollution. Specifically, the enhancement of wildfire-induced smoke aerosols increases solar absorption and scattering in the future (Fig. 6a). This reduces the incoming solar radiation reaching the surface (Fig. 6b) and induces surface cooling. With atmospheric warming and surface cooling, lower-tropospheric stability is enhanced by wildfire aerosols in the future (Fig. 6c). The smoke plumes which reach the eastern US are at an elevated altitude due to the self-lofting property of absorbing aerosols as they travel downwind, but the smoke over the western US is at near-surface elevation as it is at its source region. This can explain the more significant atmospheric stability simulated over the eastern US compared to the source regions in western US and boreal forests of Canada. Relatively stronger atmospheric stability over the eastern US imposes a stronger thermal capping that traps more anthropogenic aerosols and particulate matter near the surface over the EUS (already an emission hotspot). At the same time, future increase in wildfire emissions also leads to greater reduction in monthly rainfall (Fig. 6d) over the EUS, which may additionally strengthen the positive feedback to surface  $\text{PM}_{2.5}$  over the EUS by reducing wet

scavenging of transported wildfire smoke to the EUS. Thus, wildfire-emitted aerosols induce positive feedback on the surface  $\text{PM}_{2.5}$  concentration over the EUS through fire–climate interactions that vary on a regional scale. Moreover, the above-discussed dynamical changes in the future can also feedback these simulated thermodynamical and precipitation changes, exaggerating the enhancement in  $\text{PM}_{2.5}$  values over the EUS in the future. However, due to computational constraints, no direct quantification of the magnitude of these feedbacks (with aerosol–radiation and aerosol–cloud interactions turned off) on  $\text{PM}_{2.5}$  is performed and would be taken up in future studies.

Lastly, the reason for why the contribution of wildfire emissions to the total surface  $\text{PM}_{2.5}$  in the EUS is so substantial in the 2050s is the drastic reduction in anthropogenic contribution to the surface  $\text{PM}_{2.5}$  over the EUS in the future primarily due to policy-driven reduction in anthropogenic emissions under the RCP4.5 scenario. Specifically, the simulated ambient summer mean  $\text{PM}_{2.5}$  concentration exhibits widespread declines in the future (Supplement Fig. S4), with reduction in  $\text{PM}_{2.5}$  concentration over the eastern US in the range of  $4\text{--}15 \mu\text{g m}^{-3}$ , which is greatest within North America. Thus, a large reduction in anthropogenic contribution combined with increased downwind advection of Canadian smoke and the associated positive feedbacks can explain the projected dominance of wildfire emissions over the EUS in the future.

### 3.4 Future implications and uncertainties

However, is the simulated future enhancement in wildfire contribution over the EUS substantial enough to affect the surface  $\text{PM}_{2.5}$  values over the EUS in the future? The World Health Organization (WHO) air quality guidelines for annual and daily  $\text{PM}_{2.5}$  concentration are 10 and  $25 \mu\text{g m}^{-3}$ , respectively. As no specific guideline for seasonal-mean  $\text{PM}_{2.5}$  in the summer is available, we use the annual guideline value as a reference to understand the implication of wildfire emissions for ambient  $\text{PM}_{2.5}$  concentration in the future. Interestingly, the mean summertime  $\text{PM}_{2.5}$  concentration in the wildfire-emission-free (WEF) scenario is projected to remain within  $10 \mu\text{g m}^{-3}$  over most of North America, except for the southeastern US ( $\sim 15\%$  of the domain) (Fig. 7a). However, the ALL scenario projects an increase in the exposure concentration level such that values  $> 10 \mu\text{g m}^{-3}$  are common in Canada and the EUS in the future (Fig. 7b). Quantitatively, over Canada, the entire PDF of  $\text{PM}_{2.5}$  concentration shifts towards higher values by  $\sim 5\text{--}6 \mu\text{g m}^{-3}$ . Specifically, the modal value shifts from  $\sim 6 \mu\text{g m}^{-3}$  in 2050<sub>WEF</sub> to  $11\text{--}12 \mu\text{g m}^{-3}$  in 2050<sub>ALL</sub> (Fig. 7c), so  $\text{PM}_{2.5}$  concentration is projected to surpass the WHO guidelines over a large fraction of Canada in the future. Similarly, the entire PDF of  $\text{PM}_{2.5}$  concentration shifts towards higher values by  $\sim 2\text{--}3 \mu\text{g m}^{-3}$  over the EUS, with the mode of the PDF increasing from  $\sim 7\text{--}8 \mu\text{g m}^{-3}$  in 2050<sub>WEF</sub> to  $\sim 10\text{--}11 \mu\text{g m}^{-3}$

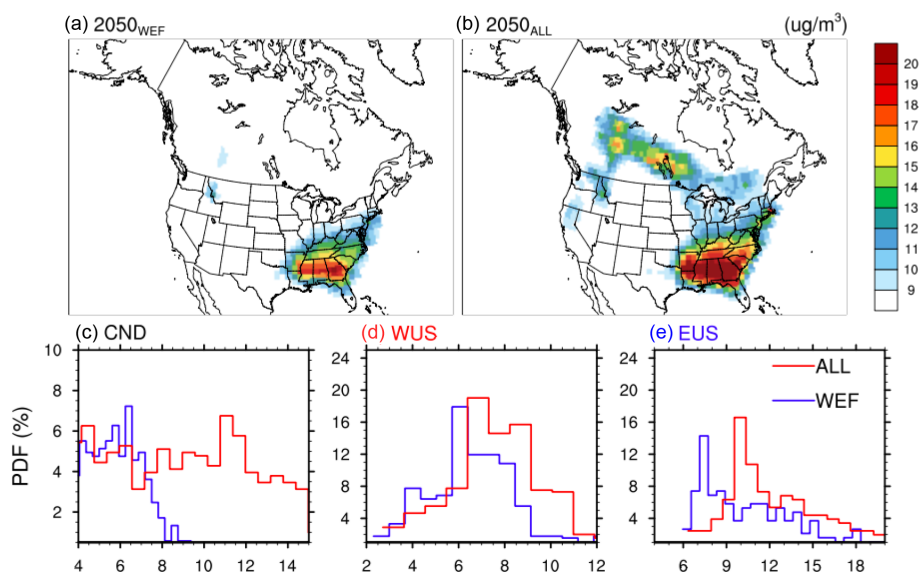


**Figure 6.** Spatial distribution of decadal-mean summer (JJA) wildfire-induced future changes ( $(2050_{\text{ALL}}-2050_{\text{WEF}})-(2000_{\text{ALL}}-2000_{\text{WEF}})$ ). (a) Aerosol absorption optical depth at 550 nm, (b) aerosol direct radiative forcing at the surface, (c) lower-tropospheric stability calculated as the difference between the potential temperature at 900 and 1000 hPa, (d) summer-averaged precipitation rates over North America. Areas marked with black dots indicate grids where changes are significant at the 95 % confidence level.

in 2050<sub>ALL</sub> (Fig. 7e). The modal value of summer mean  $\text{PM}_{2.5}$  over the WUS increases from  $\sim 6 \mu\text{g m}^{-3}$  in 2050<sub>WEF</sub> to  $\sim 7\text{--}8 \mu\text{g m}^{-3}$  in 2050<sub>ALL</sub> (Fig. 7d), although a few grid cells show  $\text{PM}_{2.5}$  values greater than  $10 \mu\text{g m}^{-3}$  (Fig. 7b).

Clearly, the climate-induced enhancement in fires and its influence via the advected wildfire smoke to the EUS can have significant implications for air quality management in the future. The  $\text{PM}_{2.5}$  enhancement in the future over the southern states within the EUS is large (Fig. 7a–b), which is consistent with the results of Figs. 3 and 4. However, the future change in burned area over the same region is negligible or mostly reducing (Fig. 1c–d). Thus, it can be argued that the simulated enhancement is mostly related to the dynamic perturbations and thermodynamical feedbacks due to wildfire emissions (Fig. 6). As the rate of anthropogenic emissions is also the highest regionally over the southeastern states, the impact of these wildfire-induced climatic feedbacks on local air quality is distinctly seen over the EUS.

Note that our simulated present-day estimates of wildfire-induced  $\text{PM}_{2.5}$  values as well as the percentage contribution of wildfire emissions are within the range of reported values in previous studies over the domain, which augment the fidelity of our future projections. Specifically, our simulated present-day estimates of wildfire-induced  $\text{PM}_{2.5}$  values are also within the range of reported values in previous studies over the domain. Reported values of wildfire-induced  $\text{PM}_{2.5}$  over the WUS during summertime vary from  $\sim 1 \mu\text{g m}^{-3}$  (Jaffe et al., 2008) to  $\sim 2 \mu\text{g m}^{-3}$  (Park et al., 2007) and  $\sim 3 \mu\text{g m}^{-3}$  (Ford et al., 2018), with the highest values documented over the Pacific Northwest and west coast regions ( $\sim 1\text{--}4 \mu\text{g m}^{-3}$ ) (O’Dell et al., 2019). The wildfire-induced  $\text{PM}_{2.5}$  over the EUS during summertime varies from  $\sim 1 \mu\text{g m}^{-3}$  (Park et al., 2007) to  $\sim 2.5 \mu\text{g m}^{-3}$  ( $\sim 3 \mu\text{g m}^{-3}$  in the southeastern US) (Ford et al., 2018). Consistently, our simulated present-day estimates of wildfire contribution values are also within the range of reported values in previous studies. For example, Meng et al. (2019) found that wildfires



**Figure 7.** Spatial distribution and probability density function of  $\text{PM}_{2.5}$  concentration in the 2050s. (a–b) Spatial distribution of decadal-average summer (JJA) mean  $\text{PM}_{2.5}$  concentration over North America in the mid-21st century from 2050<sub>WEF</sub> (wildfire-emission-free) (a) and 2050<sub>ALL</sub> (wildfire-emission-inclusive) (b). (c–e) Probability density functions (PDFs) of the same within the three regions shown in Fig. 2b for Canada (CND) (c), the western US (WUS) (d), and the eastern US (EUS) (e), respectively, for the 2050<sub>WEF</sub> (blue) and 2050<sub>ALL</sub> (red) runs. The y axis indicates the probability of occurrence of different  $\text{PM}_{2.5}$  values shown on the x axis. Only grids over land in North America are used to generate the PDFs. Note the different ranges of values shown on the y and x axis in (c)–(e). The color bar and the x axis for panels (c)–(e) indicate  $\text{PM}_{2.5}$  values.

can be the largest sectoral contributor ( $\sim 18\%$ – $59\%$ ) to the population-weighted  $\text{PM}_{2.5}$  in various subregions of Canada. Over the WUS, the present-day percentage contribution of wildfire-induced  $\text{PM}_{2.5}$  to the total  $\text{PM}_{2.5}$  is reported to be  $\sim 12\%$  (Liu et al., 2017),  $\sim 15\%$  (Park et al., 2007), and  $\sim 30\%$  (Ford et al., 2018), with higher values of  $\sim 40\%$  in the Pacific Northwest (O’Dell et al., 2019). Over the EUS our simulated values are also within the range of previously reported values of  $\sim 5\%$  (Park et al., 2007) and  $\sim 15\%$ – $18\%$  (Ford et al., 2018). However, our two-way coupled simulations illustrate that future enhancement in the wildfire-associated  $\text{PM}_{2.5}$  over the EUS could be greater compared to the western US, which is not emphasized explicitly in any of the previous studies (although Ford et al., 2018, illustrated an increase in  $\text{PM}_{2.5}$  over the mid-US and central US from Canadian fires). These could be since inclusion of the wildfire-induced climatic feedbacks in our simulation is an unprecedented exercise. Please also note that our study is focused on the JJA period, and the wildfires in the western US mainly occur during August–September, so the results should be compared consciously.

Nonetheless, inherent limitations in our simulations may introduce uncertainties in the projected future changes. For example, our reported changes in  $\text{PM}_{2.5}$  concentrations based on relatively coarse-resolution simulations and decadal averages likely represent a low-end estimate compared to changes at regional and daily/weekly scales. Moreover, our experiments do not consider the direct human influences such

as population change and socioeconomic development on wildfires, which may aggravate the increase in  $\text{PM}_{2.5}$  concentrations over the densely populated EUS in the future. Common sources of uncertainty in modeling burned area and fire emission and fire aerosol and smoke are also present in our model. Fire smoke, in particular, is extremely hard to measure and evaluate. Lastly, inherent uncertainties in the physics parameterizations used in the model, sensitivity of climate to GHG emissions, and the RCP scenarios should also be noted. Thus, ensemble modeling considering different emissions scenarios, population, and future time periods and the use of a finer spatial resolution may provide a more robust and better quantification of the wildfire-induced impact on policy-regulated improvements in  $\text{PM}_{2.5}$  over the EUS.

## 4 Conclusions

In summary, online-coupled fire–climate–ecosystem simulations project a nearly 2-fold increase in wildfire-induced summer-mean surface  $\text{PM}_{2.5}$  concentration by the mid-21st century over all of North America. In a wildfire-emission-free future, a large portion of North America will have  $\text{PM}_{2.5}$  values below the WHO guidelines. But in a future with wildfire emissions, the improvements from policy-driven reductions in anthropogenic  $\text{PM}_{2.5}$  will be compromised by the projected doubling of  $\text{PM}_{2.5}$  from wildfires. More strikingly, wildfire-induced enhancement in surface  $\text{PM}_{2.5}$  values and



percentage contribution of the wildfire emissions over the EUS could be substantial by mid-century. This is mainly because of the large enhancement in fires over North America by the 2050s and associated increase in the amount of downwind transport of smoke to the EUS. In addition, enhancement of smoke transport induces a positive climate feedback to PM<sub>2.5</sub> concentrations over the EUS by increasing the lower-tropospheric stability and reducing wet-scavenging rates. Despite the inherent limitations, this study highlights the natural versus anthropogenic contributions and the non-local nature of air pollution that can complicate regulatory strategies aimed at improving air quality over the eastern US in a warmer future.

**Code availability.** The model code and scripts are available at <https://portal.nersc.gov/project/m1660/yang560/wildfire> (Sarangi and Qian, 2023).

**Data availability.** The HMS data used in this paper are available for free through the link <https://www.ospo.noaa.gov/Products/land/hms.html> (NOAA, 2023). The model simulation data are available at <https://portal.nersc.gov/project/m1660/yang560/wildfire> (Sarangi and Qian, 2023).

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**Author contributions.** YQ, CS, and LRL designed this study. CS did the model and satellite analysis and wrote the first draft of the manuscript. YuZ performed the simulations. All authors provided inputs throughout the study and helped in the drafting and submission process.

**Competing interests.** At least one of the (co-)authors is a member of the editorial board of *Atmospheric Chemistry and Physics*. The peer-review process was guided by an independent editor, and the authors also have no other competing interests to declare.

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