Reviewer#1

This manuscript presents a modeling investigation of particulate matter (PM$_{2.5}$) changes by the mid-21st century driven by changes in wildfire smoke emissions across North America. Based on simulations with and without wildfire emissions in a coupled fire-climate-ecosystem model (RESFire-CESM), the authors reveal elevated summertime wildfire-induced PM$_{2.5}$ concentrations during 2050s over the entire North America, with most substantial increase in wildfire contribution to the total PM$_{2.5}$ across the eastern United States. The authors further attribute this remote PM$_{2.5}$ enhancement to smoke transport and positive climatic feedbacks on PM$_{2.5}$. While this study provides insights on a timely issue, it seems this study could be improved in terms of its completeness. More specifically, the proposed mechanism underlying the remote effects of wildfire emissions on PM$_{2.5}$ over southeastern US needs further verification or exploration. Therefore, I suggest to return the manuscript to the authors for major revision.

We are thankful to the reviewer for his careful reading and thoughtful suggestions. We have addressed all the concerns and provided our response to each of these points below (response in **blue** and revised text of manuscript in red font).

Main suggestions:

While the authors investigate the thermodynamical feedbacks associated with absorbing aerosols, it looks like neither the dynamical feedbacks or circulation changes under climate change are explored. Intuitively, one would expect the dynamical/circulation features to be important for the long-range transport of smoke; without a thorough analysis on the dynamical aspects, it is hard to believe that the thermodynamical feedbacks are the only or dominant mechanism underlying the projected enhancement of the remote smoke-induced PM$_5$. I suggest to 1) analyze observational data to identify circulation features that are responsible for long-range transport of western North American smoke to the southeastern US region; 2) evaluate the historical representation of such circulation features in your model; 3) investigate changes in such circulation feature between 2050s and 2000s, with and without wildfire emissions. In terms of the currently analyzed climatic feedbacks to smoke, the current interpretation of Figure 5 does not seem to be complete or robust. For example, the authors argue that “lower-tropospheric stability is enhanced by wildfire aerosols in the future”, but the changes in AAOD (Figure 5A) or stability (Figure 5C) are only significant in very small and inconsistent areas in the eastern US. In addition, how do you explain the lack of stability changes in western US despite the significant changes in AAOD? Are the changes in stability sensitive to vertical distribution of absorbing aerosols? It is even harder to believe that the changes in AAOD (Figure 5A) solely cause the changes in precipitation (Figure 5D), given their very distinct spatial patterns.

We are thankful for the reviewer’s suggestion. Actually, we discussed about the transport of enhanced smoke emission in detail and also identified it as a key cause of more wildfire-enhanced pollution over EUS compared to WUS in future (before discussing the climate feedbacks in figure 5). However, the climate-induced changes in circulation was not discussed in the original version and we have now included the same in our revised manuscript as a new figure on dynamical feedbacks.

Figure R1 below compare the decadal mean wind circulation at 850 hPa over North America for JJA season (2001-2010) from a) NCEP reanalysis and b) CESM-Resfire simulated control run simulation. The comparison illustrate that the model is able to reasonably capture the westerly jets and broad west to east circulation patterns over North America during our study season. A more detailed and comprehensive evaluation of simulated meteorology including dynamical/circulation features by the control run is illustrated in Zou et al., 2019, ACP and Zou et al., 2020, ACP.

As the background circulation is westerlies over Northern America during both present and future years, the wildfire emissions are advected from Canada and western US to eastern US. In future, the simulated speed of the westerly jet flows over Canada wildfire regions is reduced in both the scenarios (ALL and WEF). It indicates that the westerly-induced transported wildfire emissions from Canada boreal forests to the eastern half of Northern America and EUS will be slower in future compared to that in present era. On the one hand, it implies that the advection of smoke plumes will be slightly reduced in future. On the other hand, this phenomena can also contribute to the enhanced PM2.5 values at surface as these transporting plumes will be subject to relatively more boundary layer mixing over the EUS and dry deposition/settling enhances. At the same time, the westerly winds over western US below 40N is strengthened in future compared to present day which indicates more advection flux of wildfire emissions to EUS. Thus, in addition to the thermodynamical and precipitation changes, the dynamical changes in future also generates a positive feedback and provides a more solid explanation for the simulation of relatively more PM2.5 accumulation over the eastern US compared to western US in future under wildfire enhancement.

We agree with the reviewer that the elevational variation of wildfire plumes over eastern US and western US /Canada is the cause of the differences we see in lower tropospheric stability. The smoke plumes which reaches eastern US are at an elevated altitude due to self-lofting property of absorbing aerosols as they travel downwind but the smoke over western US is at near surface elevation as it is at its source region. This can explain the significant atmospheric stability simulated over the eastern US compare to the source regions in western US and boreal forests of Canada. We have accordingly included this explanation in our revised text (see below).

The difference between future and present run (due to wildfire emissions) also show that rainfall reduces in eastern US region and increases in western US region. We have revised the text to clarify that this is an additional effect on PM2.5 accumulation over Eastern US rather than the interpretation that the absorbing aerosols are causing this regional heterogeneity in precipitation change. We have added following texts and new figure in the revised manuscript.

In future, the simulated speed of the westerly jet flows over Canada wildfire regions is reduced in both the scenarios (ALL and WEF). It indicates that the westerly-induced transported wildfire emissions from Canada boreal forests to the eastern half of Northern America and EUS will be slower in future compared to that in present era. On the one hand, it implies that the advection of smoke plumes will be slightly reduced in future. But on the other hand, this phenomena can also contribute to the enhanced PM2.5 values at surface as these transporting plumes will be subject to relatively more boundary layer mixing over the EUS and dry deposition/settling enhances. At the same time, the westerly winds over western US below 40N is strengthened in future compared to present day which indicates more advection flux of wildfire emissions to EUS. Thus, the net effect is more removal of wildfire-emitted PM2.5 from WUS and more influx of wildfire-emitted PM2.5 in EUS.

Along with this 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 (Figure 6A). This reduces the incoming solar radiation reaching at the surface (Figure 6B) and induces surface cooling. With atmospheric warming and surface cooling, lower-tropospheric stability is enhanced by wildfire aerosols in the future (Figure 6C). The smoke plumes which reaches eastern US are at an elevated altitude due to self-lofting property of absorbing aerosols as they travel downwind but the smoke over 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 eastern US impose a stronger thermal capping that traps more anthropogenic aerosols and particulate matter near the surface over EUS (already an emission hotspot). At the same time, future increase in wildfire emissions also leads to greater reduction of monthly rainfall (Figure 6D) over EUS, which may additionally strengthen the positive feedback to surface PM2.5 over EUS by reducing wet scavenging of transported wildfire smoke to EUS. Thus, wildfire-emitted aerosols induce positive feedback on the surface PM2.5 concentration over EUS through fire-climate interactions that vary on a regional scale. Moreover, the above discussed dynamical changes in future can also feedback these simulated thermodynamical and precipitation changes, exaggerating the enhancement in PM2.5 values over EUS in future. However, due to computational constrains, no direct quantification of the magnitude of these feedback (with aerosol-radiation and aerosol-cloud interactions turned off) on PM2.5 is performed and would be taken up in future studies.

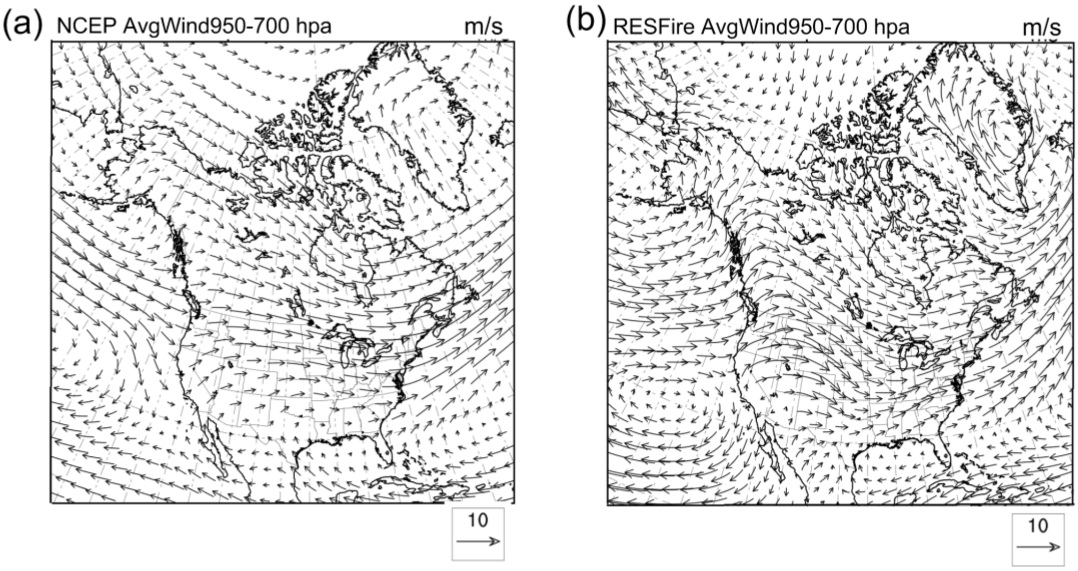


Figure R1: Spatial distribution of the decadal mean wind circulation at 850 hPa over North America for JJA season (2001-2010) from a) NCEP reanalysis and b) CESM-Resfire simulated control run simulation

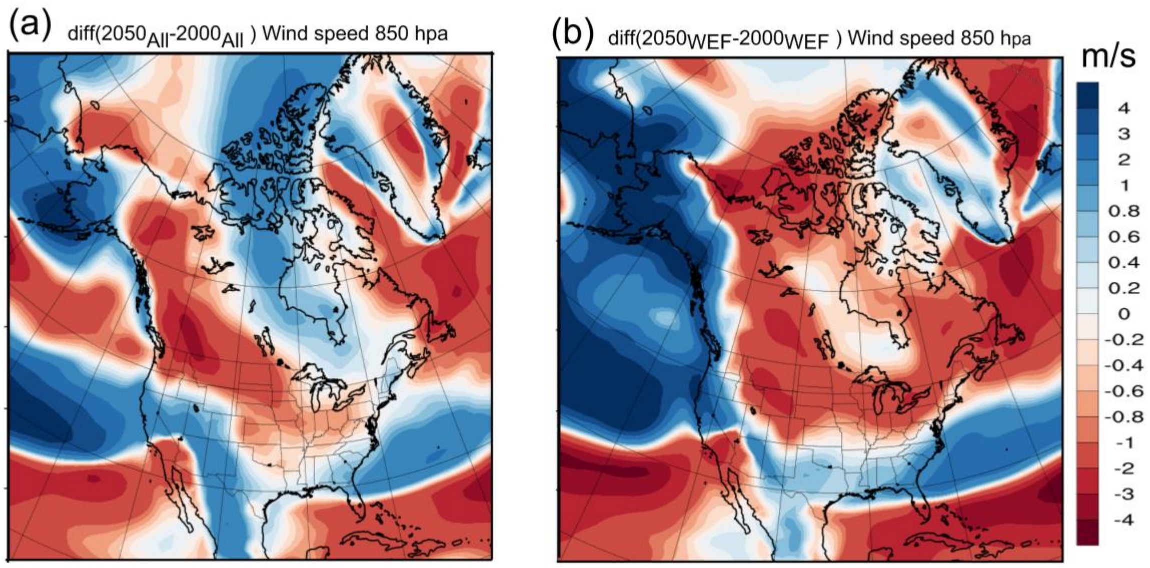


Figure 5a: Spatial distribution of decadal mean summer (JJA) wildfire-induced future changes [(2050ALL-2050WEF) – (2000ALL-2000WEF)]. A) Wind speed at 850 hpa for [(2050ALL-– 2000ALL], B) Wind speed at 850 hpa [(2050WEF) – (2000WEF)].

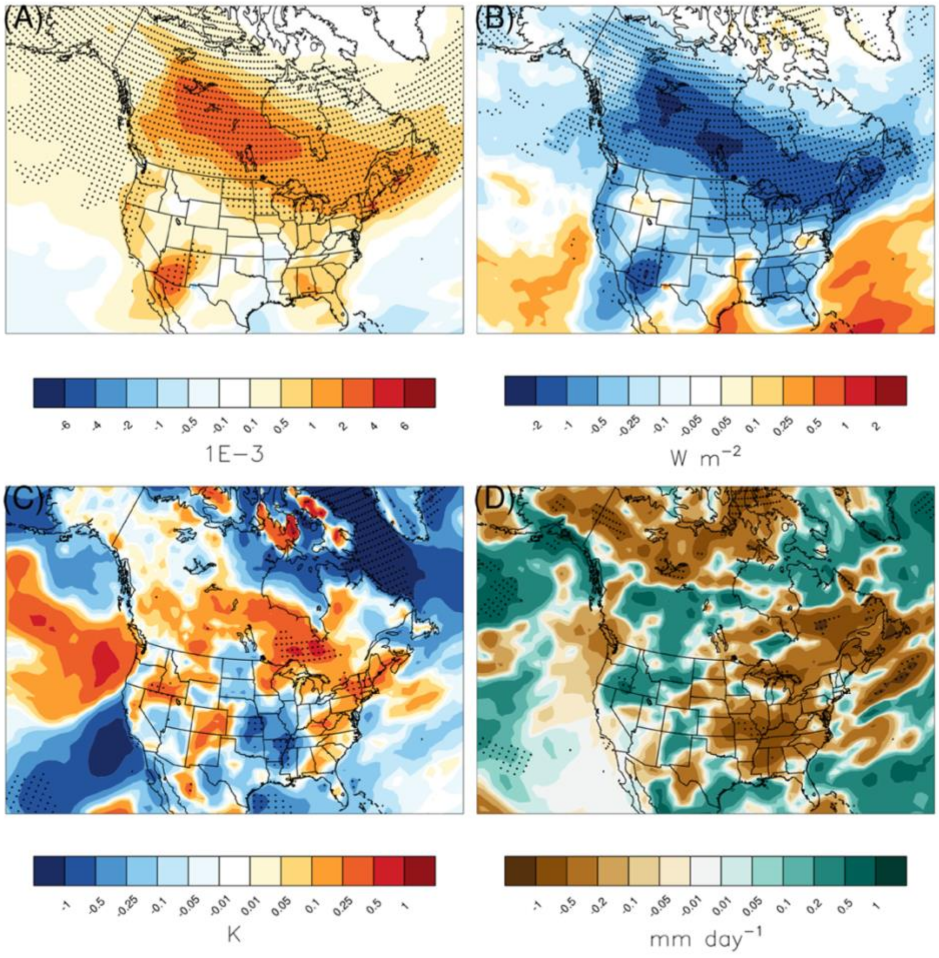


Figure 6: Spatial distribution of decadal mean summer (JJA) wildfire-induced future changes [(2050ALL-2050WEF) – (2000ALL-2000WEF)]. A) aerosol absorption optical depth at 550 nm, B)

aerosol direct radiative forcing at surface, C) lower-tropospheric stability calculated as the difference between the potential temperature at 900 hPa 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.

While the authors focus their analysis on decadal mean changes and spatial distribution of such changes, the temporal variations in PM_5 are worthy of investigation too. A natural question would arise whether we will experience elevated occurrence of extreme $PM_{2.5}$ days. For example, it would be interesting to see something similar to Figure 6 but presenting the spatio-temporal PDF of $PM_{2.5}$ from all grid cells and all days in both the historical and future simulations.

In this experiment, our aim was to understand the changes at climatic scale, so we saved our simulated output values at monthly resolution only to reduce the huge expense associated with storage and file movement for analysis. Hence, we are not able to do daily scale analysis, although the reviewer's suggestion is valid.

Does your simulation include multiple ensemble members? Will an ensemble simulation enhance the robustness of your results?

No, our simulations do not include ensemble members. More details see Zou et al., 2019, ACP and Zou et al., 2020, ACP.

In our experiment, we aim at qualitative and annual mean scale analysis of what might happen in future under climate change induced wildfire enhancement. An ensemble simulation setup can help us towards reducing the uncertainty in quantitative forecasts/analysis in this experiment. But due to computational constrains simulating ensembles was not undertaken.

Finally, while the burnt area does not increase in the southeastern US, it is possible that smoke emission still increases. Does your model account for future biomass increase and possible smoke emission rate increase?

Yes, ResFire includes for future biomass increase and smoke emission rate.

Minor suggestions:

On line 217-218, the authors attribute the inconsistency between model and satellite-derived PM_5 to the bias in the pristine region, but the scatterplot does not seem to support such bias in the low-value region.

This sentence is meant for Figure 1C. We can distinctly see a cluster of low PM2.5 biased towards satellite measurement compared to observations. We have revised the sentence now as follows for clarity.

First, the satellite-derived data has a non-zero lower bound of $PM_{2.5}$ concentrations, so the ambient background concentrations for relatively cleaner regions such as the western US may be overestimated (Figure 1C), also the sampling frequency between these datasets are different.

On line 249, it is also useful to indicate sample size.

We have included the sample size in captions

On lines 315-316, please rephrase this sentence, it is not clear what this sentence means.

We have removed the mentioned statement.

On lines 396-398, you can actually test this hypothesis with your simulations, for example by compositing absorbing aerosols in the subsequent days following fire events in Canada.

As explained above, we don’t have simulation outputs at daily resolution.

Figure 5, what statistical test did you use?

Students t-test was used.

All the data shown in Fig.5 are fire-induced differences between the 2050 scenario and the 2000 scenario as indicated in the caption. They are not temporal trends. We subtract the fire effects in the 2000s from the fire effects in the 2050s [(2050ALL-2050WEF) – (2000ALL-2000WEF)] to evaluate the fire-induced changes from the 2000s to the 2050s. The significance of these changes is calculated using the Student’s t-test between the two simulations.

Around line 450, it is also helpful to report the percentage of grids with seasonal mean PM_5 exceeding 10 µg m^{-3}.

We have included in the text.

Reviewer #2

The authors applied fire-climate-ecosystem model to study the effects on increasing wildfires on summer PM2.5 over the US. Although some good results obtained, I am more worried about the real accuracy of the model simulations, especially in the irregular wildfires occurred in the western United States, which needs to be well verified. In addition, additional analyses are needed to make the results more robust.

We are thankful to the reviewer for his thorough reading and thoughtful comments. We have provided our response to each of these points below (response in **blue** and revised text of manuscript in red font).

At the outset, we want to point out that as mentioned in our manuscript, Zou et al., 2019 have extensively evaluated the control run (2000_{ALL}) simulation of our fire model that is developed under the framework of the Community Earth System Model (CESM, http://www.cesm.ucar.edu/) against observations and previous fire modeling results. These evaluation results suggest that our fire modeling ensemble results (both burned area simulations and fire smoke impacts on air quality) under the 2000 climatological conditions (i.e., greenhouse gases/GHGs, sea surface temperature/SST, sea ice concentration/SIC, etc.) are within the uncertainty range among various satellite and ground-based datasets of the same time period.

Major comments:

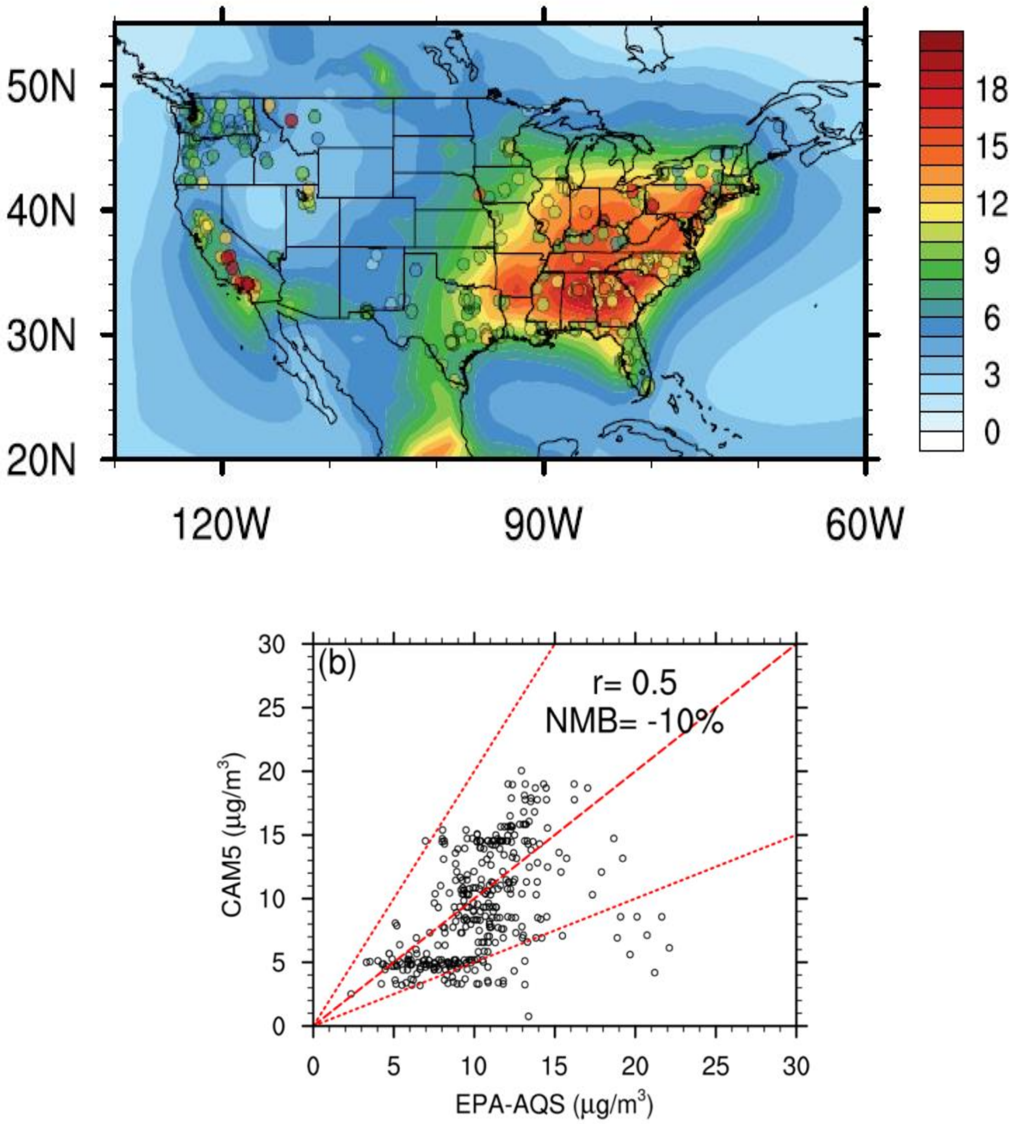
The authors are suggested to summarize the previous studies related to PM2.5 changes in the US, especially those focusing on wildfires in the Introduction.

My biggest concern is the accuracy of the model simulation results, especially for the western US, which is essential for the current study. The author simply compared the model results with a single satellite remote sensing product. Note that the sampling frequency of these two is different since there are a large number of missing values in satellite products under cloudy conditions. I suggest using ground-based observations to evaluate the model simulations from different spatiotemporal scales over North America since a rich ground-based observation network of PM2.5 concentrations and its components are available, e.g., EPA, and IMPROVE, etc.

In the revised manuscript, we have included the evaluation of simulated PM2.5 over the continental US against IMPROVE observations and the following figures and paragraph is added.

The simulated $PM_{2.5}$ has also been evaluated against the ground-based Interagency Monitoring of Protected Visual Environments (IMPROVE) data, showing similar spatial pattern and biases (10-25%) (Supplementary Figure 2). The biases are smaller over Eastern US and Southwestern US region. The simulated PM2.5 values over California matches quite well with the observed annual mean values. However, the biases over Northwestern US region are ~30-40%, a portion of which could be attributed to possible biases in model's meteorology in northwestern US region. Nonetheless, both satellite and in situ evaluation indicate 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%

to 33.3% when benchmarked against the ground-based IMPROVE data over the contiguous US (Diao et al., 2019; Val Martin et al. (2015)).

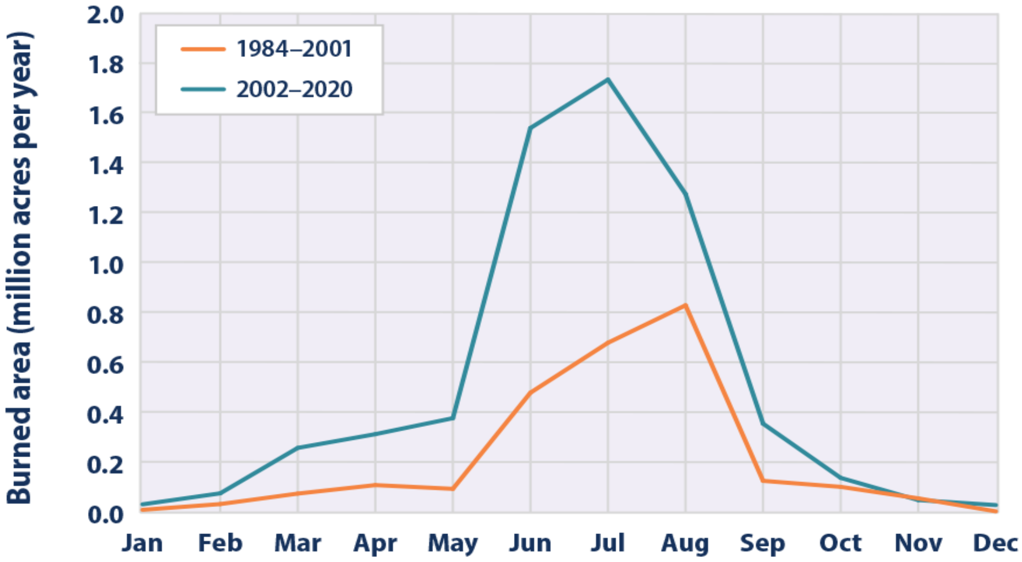


Supplementary Figure 2: Evaluation of the CAM5 simulated surface $PM_{2.5}$ ($\mu g\ m^{-3}$) with fire emissions from RESFire. Comparison of decadal-averaged (2001-2010) annual surface $PM_{2.5}$ between the simulation (shading) and the Interagency Monitoring of Protected Visual Environments (IMPROVE) data from US EPA Air Quality System (AQS) in situ observations (colored circles) in the 2000s; (b) Comparison of simulated and in-situ measured annual mean surface $PM_{2.5}$.

Another concern is that compared with summer (JJA), wildfires in recent years mostly occurred in dry autumn, e.g., California fire in 2020, which has been burning for nearly two months (September and October).

We agree that the wildfires in California in recent years are occurring in September and October, but at continental US scale, wildfire occurrence peak is actually shifting from August in 1990s to July month in 2000s. Monthly wildfire-induced burnt area statistics from EPA (Figure below) shows that JJA are the months of highest occurrence. Our simulations also replicated similar monthly variations. Hence, we used summer (JJA) months for focus of our analysis. Moreover, this monthly variation is dominated by fires in western US.

Comparison of Monthly Burned Area Due to Wildfires in the United States Between 1984–2001 and 2002–2020



Data source: MTBS (Monitoring Trends in Burn Severity). 2022. Direct download. Accessed April 2022. www.mtbs.gov/direct-download.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

Section 3.1: Suggest comparing different satellite PM2.5 and component datasets over the US since many open datasets are available. In addition, it is suggested to add a validation of a single wildfire year or month, e.g., a severe and continuous wildfire occurred in western US in September 2020.

In this experiment, our aim was to understand the changes at climatic scale, so we saved our simulated output values at a resolution of 10 year mean monthly values only, to reduce the huge expense associated with storage and file movement for analysis. Hence, we are not able to do monthly scale analysis for any specific year.

Nonetheless, as also mentioned in our manuscript at line number 185-190, the present day simulated wildfire burnt area and wildfire spatial pattern was comprehensively evaluated in the preliminary papers of CESM-RESfire simulations in Zou et al., 2019.

Zou et al. (2019) performed comprehensive evaluation of the RESFire simulated wildfire burnt area distribution, associated carbon emissions and terrestrial carbon balance to demonstrate reasonable model skill. Zou et al. (2020) compares global fire simulations by CESM-RESFire with modeling results reported in the literature to show better agreement with the GFED4.1s benchmark data and predicts 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.

Section 3.2: It will be very interesting to take a look at the Fire Burnt Area, PM2.5 changes, and related contributions caused by wildfires in the past decade (2010-2020). Wildfires in the west of US have been burning more frequently in recent years, much higher than in the first decade.

We agree that wildfire burnt area and impact in the west of US has enhanced in recent years (2000-2020) compared to 1980-2000 and is projected to even more increase in the coming decades due to warming. However, the wildfire burnt area and impact over the US between the two recent decades of 2000-2010 and 2011-2020 is more or less same. In fact, the recent EPA report (https://www.epa.gov/climate-indicators/climate-change-indicators-wildfires) illustrate that the wildfire frequency over the US in 2010-2020 is a bit less compared to the same in the decade 2000-2010.

Here, we had taken two representative decades of present climate (2000-2010) and future climate (2050-60) and made sensitivity runs (with and without wildfire effect) for both the periods, so total eight 10-year global simulations. The comparison of these two representative periods provides us the qualitative understanding on how air quality in the eastern US be affected in future under climate change induced wildfire enhancement at climatology scale. Due to computational constrains, we are unable to simulate another decade 2010-2020. Also, we feel that these additional simulations will not significantly change our conclusions and understanding.

Minor comments:

Line 172: Please spell out the JJA and check such issue throughout the paper.

We have revised.

Line 193: Figure 1

Revised.

Lines 216-217: Again, sampling frequency is also a potential reason resulting in the differences that should be discussed.

We have included.

First, the satellite-derived data has a non-zero lower bound of $PM_{2.5}$ concentrations, so the ambient background concentrations for relatively cleaner regions such as the western US may be overestimated (Figure 1C), also the sampling frequency between these datasets are different.

Figure 5: Confusing. Are these temporal trends? If not, what the significant confidence level here used and how to calculate?

All the data shown in Fig.5 are fire-induced differences between the 2050 scenario and the 2000 scenario as indicated in the caption. They are not temporal trends. We subtract the fire effects in the 2000s from the fire effects in the 2050s [(2050ALL-2050WEF) – (2000ALL-2000WEF)] to evaluate the fire-induced changes from the 2000s to the 2050s. The significance of these changes is calculated using the Student's t-test between the two simulations.