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Trends and spatial shifts in lightning fires and smoke concentrations in response to 21st century climate over the forests of the Western United States

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Abstract. Almost US$ 3bn per year is appropriated for wildfire management on public land in the United States. Recent studies have suggested that ongoing climate change will lead to warmer and drier conditions in the Western United States with a consequent increase in the number and size of wildfires, yet large uncertainty exists in these projections. To assess the influence of future changes in climate and land cover on lightning-caused wildfires in National Forests and Parks of the Western United States and the consequences of these fires on air quality, we link a dynamic vegetation model that includes a process-based representation of fire (LPJ-LMfire) to a global chemical transport model (GEOS-Chem). Under a scenario of moderate future climate change (RCP4.5), increasing lightning-caused wildfire enhances the burden of smoke fine particulate matter (PM), with mass concentration increases of ~53% by the late-21st century during the fire season. In a high-emissions scenario (RCP8.5), smoke PM concentrations double by 2100. RCP8.5 also shows large, northward shifts in dry matter burned, leading to enhanced lightning-caused fire activity especially over forests in the northern states.

1 Introduction

Both the incidence and duration of large wildfires in the forests of the western United States have increased since the mid-1980s (Westerling et al., 2006; Abatzoglou and Williams, 2016), affecting surface levels of particulate matter (Val Martin et al., 2006), with consequences for human health (Liu et al., 2017) and visibility (Spracklen et al., 2009; Ford et al., 2018). Wildfire activity is influenced by a combination of different factors, including fuel load, fire suppression practices, land use, land cover change, and meteorology (Pechony and Shindell, 2010). Over the forests of the Western United States (WUS), lightning-caused wildfires account for the majority of burned area (Abatzoglou et al., 2016) and have driven most of the recent increase in large wildfires, with human ignition contributing less than 12% to this trend (Westerling, 2016). Studies suggest that a warming climate could enhance wildfires in the WUS (Yue et al., 2013; Abatzoglou and Williams, 2016), but quantifying future wildfire activity is challenging, given uncertainties in land cover trends and in the relationships between fire and weather. Not all studies have accounted for changing land cover or have distinguished the effects of lightning fire ignitions from human-started fires. In this study, we project lightning-caused fire emissions over the National Parks and Forests of the WUS in the mid- and late- 21st century, using a dynamic global vegetation model combined with a chemical transport model. Our goal is to understand how trends in both land cover and meteorology may affect natural fire activity and smoke air quality over the 21st century.

Consistent with projections of increasing wildfire in the WUS, recent studies have also predicted enhancement of fire-generated PM under a warmer and drier climate in this region (Yue et al., 2013; Yue et al., 2014; Spracklen et al., 2009; Ford et al., 2018; Westerling et al., 2006). Some of these studies relied on statistical models that relate meteorological variables to fire metrics such as area burned; these models can then be applied to projections from climate models (Yue et al., 2013; Yue et al., 2014; Spracklen et al., 2009; Archibald et al., 2009; Wotton et al., 2003; Westerling and Bryant, 2008). However, these statistical methods do not account for changes in vegetation due to climate, increasing atmospheric CO_2 concentrations, or land use. A further weakness of these studies is that they do not consider whether enhanced fire activity in the future atmosphere may ultimately deplete the supply of woody fuels (Yue et al., 2013; Yue et al., 2014). Other studies have coupled global vegetation models to climate models to better represent such fire-vegetation-climate interactions (Chaste et al., 2018). These coupled models integrate vegetation dynamics, land-atmosphere exchanges, and other key physical processes, allowing consideration of many factors driving fire activity and smoke pollution on regional scales (Ford et al., 2018). Building on this research, we use an integrated vegetation-climate model system with these aims: (1) to clarify how changing meteorology and vegetation together drive future lightning-caused wildfire activity and (2) to provide predictions of smoke pollution at finer spatial resolution than previously. Our approach accounts for the impact of future climate and lightning fires on fuel structure, and these fine-scale predictions are of greater utility to environmental managers and especially the health impacts community.

Lightning is the predominant cause of wildfire ignition in most mountainous and forest regions of the WUS during months that have high fire frequency (Abatzoglou et al., 2016; Balch et al., 2017). In remote and mountainous terrain, anthropogenic ignitions are infrequent and >90% of total area burned is caused by lightning-started fires (Abatzoglou et al., 2016). Here we study lightning-caused fires over the National Parks and Forests of the WUS in the mid- and late- 21st century under two future climate change scenarios defined by Representative Concentration Pathways (RCPs). RCP4.5 represents a moderate pathway with gradual reduction in greenhouse gas (GHG) emissions after 2050, while RCP8.5 assumes continued increases in GHGs throughout

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the 21st century. We use the Lund-Potsdam-Jena-Lausanne-Mainz (LPJ-LMfire) Dynamic Global Vegetation Model (Pfeiffer et al., 2013) to simulate dynamic fire-vegetation interactions under future climate. LPJ-LMfire, which has been used previously to investigate historical fire activity (e.g., Chaste et al., 2018), is applied here to estimate natural fire emissions under future climate simulated by the Goddard Institute for Space Studies (GISS) Model E climate model.

July, August, and September (JAS) are the months of greatest fire activity in WUS forests (Park et al., 2003) and the focus of our study. We limit the spatial extent of our analyses to the National Parks and Forests of the WUS, here defined as 31°N – 49°N, 100°W – 125°W. For RCP4.5, the GISS model predicts a statistically significant increase in surface temperature of 1.4 K averaged over the entire region by 2050 during JAS; for RCP8.5, the mean JAS temperature increase is 3.7 K by 2100. In both future climate scenarios, significant precipitation decreases of ~20% by 2100 are simulated. Several studies have predicted future increases in lightning due to climate change (e.g., Price and Rind, 1994a,). However, the relationship between lightning flash rate and meteorology is poorly constrained in models and depends largely on physical parameters such as cold cloud thickness, cloud top height, or convective available potential energy. In our study, we use the convective mass flux from the GISS model to calculate lightning density in terms of flashes km^{-2} day^{-1}. Unlike surface temperature and precipitation, we find that average lightning density over the West does not change significantly during the 21st century, as described in Fig. S1.

LPJ-LMfire simulates wildfire emissions of black carbon (BC) and organic carbon (OC) particles, which are then passed to the global atmospheric chemistry-transport model GEOS-Chem, to simulate the transport and distribution of wildfire smoke across the West. For each RCP, LPJ-LMfire simulates vegetation dynamics and fire continuously for the period 2006-2100, with

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monthly resolution. For reasons of computational demand, we were limited to conducting two time-slice simulations with GEOS-Chem focused around 2010 and 2100, with each time slice covering 5 continuous years. For further details, see Methods section below.

2 Methods

We quantify the effects of changing climate on area burned and fire emissions caused by lightning over the National Forests in the WUS using the LPJ-LMfire model (Pfeiffer et al., 2013), driven by meteorological fields from the GISS-E2-R climate model (Nazarenko et al., 2015). Natural wildfire emissions of dry matter burned calculated by LPJ-LMfire are then passed to GEOS-Chem, a 3-D chemical transport model, to simulate the transport of wildfire smoke across the WUS.

2.1 LPJ-LMfire

The LPJ-LMfire dynamic vegetation model is driven by gridded climate, soil, land use fields, and atmospheric CO_2 concentrations, and simulates vegetation structure, biogeochemical cycling, and wildfire (Pfeiffer et al., 2013; Sitch et al., 2003). Wildfires are simulated based on processes including explicit calculation of lightning ignitions, the representation of multi-day burning and coalescence of fires, and the calculation of rates of spread in different vegetation types (Pfeiffer et al., 2013). The climate anomaly fields from the GISS-E2-R climate model used to prepare a future scenario for LPJ-LMfire are monthly mean surface temperature, diurnal temperature range (i.e., the difference between monthly mean daily maximum and daily minimum temperatures), total monthly precipitation, number of days in the month with precipitation greater than 0.1 mm, monthly mean total cloud cover fraction, and monthly mean surface wind speed. This version of the GISS model was configured for Phase 5 of the Coupled Model Intercomparison

Project (CMIP5) (Nazarenko et al., 2015). Lightning strike density for application in LPJ-LMfire is calculated using the GISS convective mass flux following the empirical parameterization of Magi, 2015. We run LPJ-LMfire on a 0.5°×0.5° global grid, though for this study only results over the National Parks and Forests of the WUS are analyzed.

The GISS-E2-R meteorology used here covers the period 1801-2100 at a resolution of 2° latitude x 2.5° longitude. The start year of the two climate scenarios, RCP4.5 and RCP8.5, is 2006. The two RCPs capture a range of possible climate trajectories over the 21st century, with radiative forcings at 2100 relative to pre-industrial values of +4.5 W m^{-2} for RCP4.5 and +8.5 W m^{-2} for RCP8.5. From 2011 to 2015, the greenhouse gas concentrations of the two scenarios are nearly identical. To downscale the GISS meteorological fields to finer resolution for LPJ-LMfire, we first calculate the 2010-2100 monthly anomalies relative to the average over the 1961-1990 period, and then add the resulting timeseries to a high-resolution observationally based climatology at 0.5° latitude × 0.5° longitude spatial resolution. The climatology was prepared using the datasets including WorldClim 2.1, Climate WNA, CRU CL 2.0, Wisconsin HIRS Cloud Climatology, and LIS/OTD, as described in Pfeiffer et al., 2013. The LPJ-LMfire simulations used here cover the period 2006-2100 at a monthly timestep. Future land use scenarios applied follow those in CMIP5, in which the extent of crop and pasture cover in the WUS increases by 30% in future climates (Brovkin et al., 2013; Kumar et al., 2013).

Passive fire suppression results from landscape fragmentation caused by land use (e.g., for crop and grazing land, roads, and urban areas), and this influence on fire activity is included in the LPJ-LMfire simulations (Pfeiffer et al., 2013). The model does not, however, consider the active fire suppression practiced throughout much of the WUS. We therefore limit our study to wildfire activity on the National Park and Forest lands of the WUS that are dominated by lightning fires

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and where land use for agriculture and urban areas is minimal. To focus only on National Park and Forest lands, we apply a 0.5° × 0.5° raster across the WUS that identifies the fraction of each grid cell that belongs to a National Forest or National Park, and we consider only these areas in our analysis.

2.2 Fire emissions

Fuel biomass in LPJ-LMfire is discretized by plant functional type (PFT) into specific live biomass and litter categories, and across four size classes for dead fuels. The model simulates monthly values of total dry matter burned for nine PFTs as in Pfeiffer et al., 2013. To pass LPJ-LMfire biomass burning emissions to GEOS-Chem, we first reclassify these nine PFTs into the six land cover types considered by GEOS-Chem. See Table 2 for a summary of the reclassification scheme. Tropical broadleaf evergreen, tropical broadleaf raingreen, and C_4 grasses are not simulated by LPJ-LMfire in the National Parks and Forests of the WUS. Emission factors based on the six land cover types in GEOS-Chem are then applied to dry matter burned from LPJ-LMfire, resulting in monthly BC and OC emissions over National Forests. These factors are from Akagi et al., 2011. As lightning-started wildfires are dominant over the WUS forests, an evaluation of fire emissions over National Park and Forest lands from the LPJ-LMfire model against the Global Fire Emissions Database (GFED4s) inventory (Giglio et al., 2013) is included in the Supplement (Fig. S2).

2.3 GEOS-Chem

We use the GEOS-Chem chemical transport model (version 12.0.1; http://acmg.seas.harvard.edu/geos/). For three time slices including the present day, mid- and late-21st century, we compare the five-year averaged (i.e., 2011-2015, 2051-2055, 2096-2100) living biomass and lightning fire emissions from the continuous LPJ-LM simulations with ten-year averages (i.e., 2006-2015, 2046-2055, 2091-2100). We find differences of less than 20% caused by extending the length of the time slices. We therefore perform two five-year time slice simulations for each RCP, covering the present day (2011-2015) and the late-21st century (2096-2100). For each time slice, we first carry out a global simulation at 4° latitude x 5° longitude spatial resolution, and then downscale to 0.5° × 0.625° over the WUS via grid nesting over the North America domain. For computational efficiency, we use the aerosol-only version of GEOS-Chem, with monthly mean oxidants archived from a full-chemistry simulation, as described in Park et al., 2004. The GEOS-Chem simulations are driven with present-day MERRA-2 reanalysis meteorology from NASA/GMAO (Gelaro et al., 2017) to isolate the effect of changing wildfires on U.S. air quality. The simulations include emissions of all primary PM and the gas-phase precursors to secondary particles, with non-fire particle sources comprising fossil fuel combustion from transportation, industry, and power plants from the 2011 EPA NEI inventory. In the future time slices, non-fire emissions remain fixed at present-day levels.

Our study focuses on carbonaceous PM (smoke PM; BC+OC), which are the main components in wildfire smoke (Chow et al., 2011). For the present day, we apply 5-year (2011-2015) averaged GFED4s emissions to those regions that fall outside National Forests and temporally changing LPJ-LMfire emissions from the two RCPs within the Forests (Figs. S3-S4). Implementing the combined emissions allow us to further validate the simulated results in this study using observations. For the future time slices, we assume that fires outside the National Forests remain at present-day levels, and we again combine the 2011-2015 GFED4s fire emissions with the temporally changing, future LPJ-LMfire emissions over the National Forests.

3 Results

3.1 Spatial shifts in fire activity

Under both RCPs, 21st century climate change and increasing atmospheric CO_2 concentrations lead to shifts in the distribution of total living biomass and dry matter burned. Fig. 1 shows the changes in monthly mean temperature and precipitation averaged zonally over grid cells at each 1° latitude of the West, relative to the present day, defined as ~2010. Peak temperature enhancements in JAS occur between 36°-42° N for ~2050 and ~2100 in both RCPs, with a maximum enhancement of 4 °C for RCP4.5 and 6 °C for RCP8.5 in 2100. Significant decreases in JAS precipitation occur between 33°-45° N under RCP4.5 and at latitudes north of 39° N under RCP8.5 for ~2100. The maximum decrease in monthly precipitation over the West is ~40 kg m^{-2} (~60%) in JAS under both RCPs. These warmer and drier conditions favor fire activity under future climate.

Fires and smoke production are dependent on fuel load, and throughout the 21st century, total living biomass in the WUS is primarily concentrated in northern forests (Fig. 2). For RCP4.5, living biomass exhibits significant enhancements in U.S. National Parks and Forests at latitudes north of 43° N in the 2050 time slice and north of 45° N in the 2100 time slice. North of 46° N, the change in living biomass at 2100 (~0.4 kg C m^{-2}) is double that at 2050 (~0.2 kg C m^{-2}). At latitudes south of 40°N, living biomass in RCP4.5 is generally invariant over the 21st century. In RCP8.5, living biomass also increases significantly near the Canadian border – e.g., as much as ~0.2 kg C m^{-2} for the 2050 time slice and ~0.4 kg C m^{-2} for the 2100 time slice, relative to the present day. In contrast, at latitudes between 42°-47° N in RCP8.5, total living biomass decreases by as much as -0.6 kg C m^{-2} for ~2100. For both RCPs, these mid-century and late-century changes in total living biomass are significant ($p < 0.05$) across nearly all latitudes. In RCP4.5, the spatial shifts of total living biomass are relatively weak from 2050 to 2100, consistent with the moderate climate scenario with gradual reduction in greenhouse gas emissions after 2050. However, under the continued-emissions climate scenario RCP8.5, total living biomass in these forests first increases by 2050 and then decreases by ~10% by 2100, indicating a strongly disturbed vegetation system due to climate change. Despite this decrease, living biomass in this scenario is still abundant in the West in 2100, especially over the northern forests (not shown), suggesting that future climate change will not limit fuel load. Table 1 summarizes these results.

LPJ-LMfire simulates boreal needleleaf evergreen and boreal and temperate summergreen (broadleaf) trees as the dominant plant functional types (PFTs) in the National Parks and Forests of the WUS; these PFTs together account for ~90% of the total biomass in our study domain. Changes over the 21st century (Fig. 2) reflect the changes in the growth and distribution of these PFTs, with increases in living biomass in the north and decreases in the south in both RCP scenarios (Fig. S5). In the 2100 time slice, vegetation shifts further north than in the 2050 time slice. The reasons for this shift can be traced to the climate regimes favored by different vegetation types, with temperate and boreal trees showing moderate to strong inclination in their growth along the north-south temperature gradient (Aitken et al., 2008). For example, the temperate broadleaf summergreen PFT favors regions with moderate mean annual temperatures and distinct warm and cool seasons (Jarvis and Leverenz, 1983), while boreal needleleaf evergreen generally occurs in colder climate regimes (Aerts, 1995). With rising temperatures, the living biomass of temperate summergreen trees increases in most states in the WUS, with maximum enhancement of +1.0 kg C m^{-2} in western Washington, northern Montana, and Idaho by 2100 in RCP8.5 relative to 2010. Decreases in this vegetation type for this scenario occur in the south, as much as -0.5 kg C m^{-2} in New Mexico. In contrast, boreal trees increase in only a few regions in the far north, with a

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substantial contraction in their abundance over much of the West, as much as -4.0 kg C m^{-2} for boreal needleleaf evergreen by 2100 in RCP8.5 over the northern forests.

Simulated area burned from lightning-ignited fires in the National Parks and Forests of the WUS increases by ~30% by ~2050, and by ~50% by ~2100 for both RCPs (not shown), comparable to the predicted 78% increase in lightning-caused area burned in the U.S. under a doubled CO_2 climate by Price and Rind, 1994b. That study, however, projected an increase in lightning flashes and did not consider changing land cover. The changes we calculate at 2050 are also within the range of previous studies using statistical methods for this region (e.g., 54% in Spracklen et al., 2009 and 10-50% in Yue et al., 2013). Fig. 2 further shows that dry matter burned, a function of both area burned and fuel load, increases relative to the present at most latitudes at both 2050 and 2100 and in both RCPs. Year-to-year variations in dry matter burned are greater than those in living biomass due to variations in the meteorological conditions driving fire occurrence. Previous studies have found that interannual variability in wildfire activity is strongly associated with regional surface temperature (Westerling et al., 2006; Yue et al., 2013). We show here that although total living biomass mostly decreases at latitudes ~45° N by ~2100 under RCP8.5, the peak enhancements in dry matter burned also occur at these latitudes, indicating that the modeled changes in fire activity are driven by changes in meteorological conditions that favor fire, as well as by shifts towards more pyrophilic landscapes such as open woodlands and savannas. As with biomass, lighting-caused fires also shift northward over the 21^{st} century, especially in RCP8.5. In this scenario, dry matter burned increases by as much as 35 g m^{-2} mon^{-1} across 40°-48°N at ~2100 compared to the present day. By 2100, the fire-season total dry matter burned over the forests in the West increases by 24.58 Tg/JAS (111%) under RCP4.5 and by 50.00 Tg/JAS (161%) in RCP8.5 (Table 1).

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The spatial distributions of changes in total living biomass and dry matter burned are shown in Fig. 3. Under RCP4.5, moderate decreases in total living biomass (by as much as -2.5 kg C m^{-2}) and increases in dry matter burned by 2100 (up to ~70 g m^{-2} mon^{-1}) are concentrated in central Idaho, Wyoming, and Colorado. Large declines in total living biomass and enhancements in dry matter burned occur in the forests of Idaho and Montana by 2100 under RCP8.5, with a hotspot of -5.0 kg C m^{-2} in biomass and +100 g m^{-2} mon^{-1} in dry matter burned in Yellowstone National Park. Similar trends in total living biomass and dry matter burned are also predicted for the Sierra Nevada (SN) region in California (Fig. S6). As shown in Table 1, predicted changes in dry matter burned over the SN forests by 2050 are 17-44%, comparable to the calculated future increases of 30-50% by Yue et al., 2014. We find significant increases in dry matter burned of 81% by 2100 under RCP8.5 in this region. Our results suggest that even as future climate change diminishes vegetation biomass in some regions of the WUS, sufficient fuel still exists to allow increases in fire activity and dry matter burned.

3.2 Smoke PM

Given the large uncertainty in secondary aerosol formation within smoke plumes (Ortega et al., 2013), we assume that smoke PM mainly consists of primary BC and OC. We calculate emissions of fire-specific BC and OC by combining the estimates of the dry matter burned with emissions factors from Akagi et al., 2011, which are dependent on land cover type. Application of these emissions to GEOS-Chem allows us to simulate the transport and distribution of smoke PM across the WUS.

With increasing lightning fire activity in most of the National Park and Forest areas of the WUS over the 21st century (Fig. 3), smoke PM shows modest enhancement for RCP4.5, but more substantial increases for RCP8.5 (Fig. 4). Smoke PM enhancements in RCP4.5 occur primarily

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over the forests along the state boundaries of Idaho, Montana, and Wyoming, with large increases by as much as ~10 μg m^{-3} in Yellowstone National Park. Scattered increases in smoke PM in RCP4.5 are also predicted over the forests in northern Colorado, northern California, western Oregon, and central Arizona. In RCP8.5, smoke PM enhancements are widespread over the northern states of the WUS by 2100, with significant increases in regions east of the Rocky Mountains. Increased fire activity and large smoke PM enhancements are seen by 2100 in RCP8.5, including large areas of the Flathead, Nez Perce, Clearwater, Arapaho, and Roosevelt National Forests. Particularly large increases – as much as ~40 μg m^{-3}– occur in Yellowstone National Park. The increases in fire in these forests significantly influences air quality over the entire area of Idaho, Montana, Wyoming, and Colorado, with effects extending eastward to Nebraska and the Dakotas. Increased smoke PM is also predicted over the Sierra Nevada in both RCPs. In RCP4.5, average smoke PM over the entire WUS increases by 53% compared to present (Table 1). For RCP8.5, smoke PM more than doubles (109% increase) at ~2100.

4 Discussion

We apply a coupled modeling approach to investigate the impact of changes in climate and vegetation on future lightning-caused wildfires and smoke pollution across the WUS in the 21st century. For RCP4.5, the late-21st century lightning-caused wildfire-specific smoke PM in the West increases ~53% relative to present. Comparable fire activity between 2050 and 2100 reflect the effectiveness of the emission reduction strategies after 2050 under RCP4.5, as temperature changes across the West are relatively flat from 2050 to 2100, with a nearly constant area-averaged mean annual temperature of ~19.2°C. In RCP8.5, mean annual temperatures continue increasing over the second half of the 21st century across the West, nearly 2.1°C from 2050, and wildfire-

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specific PM concentrations double by 2100.

In table S1 we compare predictions in this study with previous fire estimates under future climate. A difference between these studies and ours is that we consider only changes in fire activity over the National Parks and Forests while others examine changes over the whole WUS. However, we find that in the GFED4s inventory, present-day fire emissions outside these federally managed areas contribute less than 1% of DM burned. Also, the fact that lightning is the dominant driver of wildfire activity over the WUS forests (Balch et al., 2017) allows a reasonable comparison of the estimates in this study with those in previous studies that include both lightning and human-started fires over the West.

Table S1 shows that fire activity in the U.S. is predicted to increase in all studies cited. However, the projected changes in fire metrics such as area burned or in emissions or concentrations of smoke vary greatly across studies, from ~10-300% relative to present-day values. These discrepancies arise from differences in the methodologies, fire assumptions, and future scenarios applied. The ~80% increases in smoke emissions that we project by 2050 is generally lower than estimates in previous statistical studies (e.g., 150-170% in Yue et al., 2013 or 100% in Spracklen et al., 2009), but comparable to the predicted 78% increase in lightning-caused area burned in the U.S. under a doubled CO_2 climate by Price and Rind, 1994b, which did not account for vegetation changes due to climate change or changing CO_2. In contrast, the ~80% increase in smoke emissions in this study at ~2050 are substantially higher than the ~40% increases predicted by Ford et al., 2018 over the West, though the magnitudes of emission changes in the two studies are similar. As in our study, Ford et al., 2018 relied on a land cover model, but they also attempted to account for the influence of future changes in meteorology and population on the suppression and ignition of fires. Ford et al., 2018 predicted scattered emission increases of 40-45% over the

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West and a large increase of 85-220% over the Southeast due to increasing population and the role of human ignition. However, human activities have diverse impacts on wildfires, and those impacts are a function of land management policy, economics, and other social trends, making it challenging to predict how trends in human ignitions, fuel treatment, and fire suppression will evolve in the future (Fusco et al., 2016). In our study, we confine our focus to fires in National Parks and Forests in the West, where human activities such as landscape fragmentation through land use are less important. We further find that the patterns of increasing fire emissions by 2100 in our study – i.e., over the forests in northern Idaho, western Montana, and over the U.S. Pacific Northwest – are similar to those predicted by other studies, including Rogers et al., 2011 and Ford et al., 2018. Our study also predicts significantly elevated smoke PM in Utah, Wyoming, and Colorado in the late-21st century under RCP8.5 and in regions east of the Rocky Mountains because of the prevailing westerly winds.

The following limitations apply to our study. The vegetation model simulations of biomass and fire are driven by meteorology from just one climate model, GISS-E2-R. Over the WUS, this model simulates future temperature changes at the low end of projections by the CMIP5 ensemble, making our predictions of future fire conservative (Sheffield et al., 2013; Ahlström et al., 2012; Rupp et al., 2013). Anthropogenic ignitions are not considered in this study, but fire behavior and therefore burned area are primarily governed by meteorology and fuel structure, both of which are simulated by LPJ-LMfire. The fire simulations are performed on a 0.5°×0.5° grid, which cannot capture some the fine-grain structure of the complex topography and sharp ecotones present in our study area (e.g., Shafer et al., 2015). Our study also does not consider the effects of future climate change on the transport or lifetime of smoke PM. Previous work, however, has shown that such effects on smoke PM are likely to be small relative to the effect of changing wildfire activity

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(Spracklen et al., 2009).

Within these limitations, our results highlight the vulnerability of the WUS to lightning-caused wildfire in a changing climate. Even though a changing climate decreases the living biomass in some regions, we find that ample vegetation exists to fuel increases in fire activity and smoke. Especially strong enhancements in smoke PM occur in the Northern Rockies in the late-21st century under both the moderate and strong future emissions scenarios, suggesting that climate change will have a large, detrimental impact on air quality, visibility, and human health in a region valued for its National Forests and Parks. Our study thus provides a resource for environmental managers to better prepare for air quality challenges under a future climate change regime.

Data availability

Data related to this paper may be requested from the authors.

Author contributions

Y.L. conceived and designed the study, performed the GEOS-Chem simulations, analyzed the data, and wrote the manuscript, with contributions from all coauthors. J.O.K. performed the LPJ-LMfire simulations.

Competing interests

The authors declare that they have no competing interest.

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References

Abatzoglou, J. T., Kolden, C. A., Balch, J. K., and Bradley, B. A.: Controls on interannual variability in lightning-caused fire activity in the western US, Environmental Research Letters, 11, 045005, 2016.

Abatzoglou, J. T., and Williams, A. P.: Impact of anthropogenic climate change on wildfire across western US forests, Proceedings of the National Academy of Sciences, 113, 11770-11775, 2016.

Aerts, R.: The advantages of being evergreen, Trends in ecology & evolution, 10, 402-407, 1995.

Ahlström, A., Schurgers, G., Arneth, A., and Smith, B.: Robustness and uncertainty in terrestrial ecosystem carbon response to CMIP5 climate change projections, Environmental Research Letters, 7, 044008, 2012.

Aitken, S. N., Yeaman, S., Holliday, J. A., Wang, T., and Curtis-McLane, S.: Adaptation, migration or extirpation: climate change outcomes for tree populations, Evolutionary applications, 1, 95-111, 2008.

Akagi, S., Yokelson, R. J., Wiedinmyer, C., Alvarado, M., Reid, J., Karl, T., Crounse, J., and Wennberg, P.: Emission factors for open and domestic biomass burning for use in atmospheric models, Atmospheric Chemistry and Physics, 11, 4039-4072, 2011.

Archibald, S., Roy, D. P., van Wilgen, B. W., and Scholes, R. J.: What limits fire? An examination of drivers of burnt area in Southern Africa, Global Change Biology, 15, 613-630, 2009.

Balch, J. K., Bradley, B. A., Abatzoglou, J. T., Nagy, R. C., Fusco, E. J., and Mahood, A. L.: Human-started wildfires expand the fire niche across the United States, Proceedings of the National Academy of Sciences, 114, 2946-2951, 2017.

Brovkin, V., Boysen, L., Arora, V., Boisier, J., Cadule, P., Chini, L., Claussen, M., Friedlingstein, P., Gayler, V., and Van Den Hurk, B.: Effect of anthropogenic land-use and land-cover changes on climate and land carbon storage in CMIP5 projections for the twenty-first century, Journal of Climate, 26, 6859-6881, 2013.

Chaste, E., Girardin, M. P., Kaplan, J. O., Portier, J., Bergeron, Y., and Hély, C.: The pyrogeography of eastern boreal Canada from 1901 to 2012 simulated with the LPJ-LMfire model, Biogeosciences, 15, 1273-1292, 10.5194/bg-15-1273-2018, 2018.

Chow, J. C., Watson, J. G., Lowenthal, D. H., Chen, L.-W. A., and Motallebi, N.: PM2. 5 source profiles for black and organic carbon emission inventories, Atmospheric Environment, 45, 5407-5414, 2011.

Ford, B., Val Martin, M., Zelasky, S., Fischer, E., Anenberg, S., Heald, C., and Pierce, J.: Future fire impacts on smoke concentrations, visibility, and health in the contiguous United States, GeoHealth, 2, 229-247, 2018.

Fusco, E. J., Abatzoglou, J. T., Balch, J. K., Finn, J. T., and Bradley, B. A.: Quantifying the human influence on fire ignition across the western USA, Ecological applications, 26, 2390-2401, 2016.

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G., and Reichle, R.: The modern-era retrospective analysis for research and applications, version 2 (MERRA-2), Journal of Climate, 30, 5419-5454, 2017.

Giglio, L., Randerson, J. T., and van der Werf, G. R.: Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4), Journal of Geophysical Research: Biogeosciences, 118, 317-328, 2013.

https://doi.org/10.5194/acp-2020-80
Preprint. Discussion started: 20 February 2020

Jarvis, P., and Leverenz, J.: Productivity of temperate, deciduous and evergreen forests, in: Physiological plant ecology IV, Springer, 233-280, 1983.

Kumar, S., Dirmeyer, P. A., Merwade, V., DelSole, T., Adams, J. M., and Niyogi, D.: Land use/cover change impacts in CMIP5 climate simulations: A new methodology and 21st century challenges, Journal of Geophysical Research: Atmospheres, 118, 6337-6353, 2013.

Liu, J. C., Wilson, A., Mickley, L. J., Dominici, F., Ebisu, K., Wang, Y., Sulprizio, M. P., Peng, R. D., Yue, X., and Son, J.-Y.: Wildfire-specific Fine Particulate Matter and Risk of Hospital Admissions in Urban and Rural Counties, Epidemiology (Cambridge, Mass.), 28, 77-85, 2017.

Magi, B. I.: Global Lightning Parameterization from CMIP5 Climate Model Output, Journal of Atmospheric and Oceanic Technology, 32, 434-452, 10.1175/jtech-d-13-00261.1, 2015.

Nadelhoffer, K. J., Emmett, B. A., Gundersen, P., Kjønaas, O. J., Koopmans, C. J., Schleppi, P., Tietema, A., and Wright, R. F.: Nitrogen deposition makes a minor contribution to carbon sequestration in temperate forests, Nature, 398, 145, 1999.

Nazarenko, L., Schmidt, G., Miller, R., Tausnev, N., Kelley, M., Ruedy, R., Russell, G., Aleinov, I., Bauer, M., and Bauer, S.: Future climate change under RCP emission scenarios with GISS ModelE2, Journal of Advances in Modeling Earth Systems, 7, 244-267, 2015.

Ortega, A., Day, D., Cubison, M., Brune, W., Bon, D., De Gouw, J., and Jimenez, J.: Secondary organic aerosol formation and primary organic aerosol oxidation from biomass-burning smoke in a flow reactor during FLAME-3, Atmospheric Chemistry and Physics, 13, 11551-11571, 2013.

Park, R. J., Jacob, D. J., Chin, M., and Martin, R. V.: Sources of carbonaceous aerosols over the United States and implications for natural visibility, Journal of Geophysical Research: Atmospheres, 108, 2003.

Park, R. J., Jacob, D. J., Field, B. D., Yantosca, R. M., and Chin, M.: Natural and transboundary pollution influences on sulfate-nitrate-ammonium aerosols in the United States: Implications for policy, Journal of Geophysical Research: Atmospheres, 109, 2004.

Pechony, O., and Shindell, D. T.: Driving forces of global wildfires over the past millennium and the forthcoming century, Proceedings of the National Academy of Sciences, 107, 19167-19170, 2010.

Pfeiffer, M., Spessa, A., and Kaplan, J. O.: A model for global biomass burning in preindustrial time: LPJ-LMfire (v1. 0), Geoscientific Model Development, 6, 643-685, 2013.

Price, C., and Rind, D.: Possible implications of global climate change on global lightning distributions and frequencies, Journal of Geophysical Research: Atmospheres, 99, 10823-10831, 1994a.

Price, C., and Rind, D.: The impact of a 2× CO2 climate on lightning-caused fires, Journal of Climate, 7, 1484-1494, 1994b.

Rogers, B. M., Neilson, R. P., Drapek, R., Lenihan, J. M., Wells, J. R., Bachelet, D., and Law, B. E.: Impacts of climate change on fire regimes and carbon stocks of the US Pacific Northwest, Journal of Geophysical Research: Biogeosciences, 116, 2011.

Rupp, D. E., Abatzoglou, J. T., Hegewisch, K. C., and Mote, P. W.: Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA, Journal of Geophysical Research: Atmospheres, 118, 10,884-810,906, 2013.

Shafer, S. L., Bartlein, P. J., Gray, E. M., and Pelltier, R. T.: Projected Future Vegetation Changes for the Northwest United States and Southwest Canada at a Fine Spatial Resolution

Using a Dynamic Global Vegetation Model, PLoS One, 10, e0138759, 10.1371/journal.pone.0138759, 2015.

Sheffield, J., Barrett, A. P., Colle, B., Nelun Fernando, D., Fu, R., Geil, K. L., Hu, Q., Kinter, J., Kumar, S., and Langenbrunner, B.: North American climate in CMIP5 experiments. Part I: Evaluation of historical simulations of continental and regional climatology, Journal of Climate, 26, 9209-9245, 2013.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K., and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, Global Change Biology, 9, 161-185, 10.1046/j.1365-2486.2003.00569.x, 2003.

Spracklen, D. V., Mickley, L. J., Logan, J. A., Hudman, R. C., Yevich, R., Flannigan, M. D., and Westerling, A. L.: Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States, Journal of Geophysical Research: Atmospheres, 114, 2009.

Val Martin, M., Honrath, R., Owen, R. C., Pfister, G., Fialho, P., and Barata, F.: Significant enhancements of nitrogen oxides, black carbon, and ozone in the North Atlantic lower free troposphere resulting from North American boreal wildfires, Journal of Geophysical Research: Atmospheres, 111, 2006.

Westerling, A., and Bryant, B.: Climate change and wildfire in California, Climatic Change, 87, 231-249, 2008.

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., and Swetnam, T. W.: Warming and earlier spring increase western US forest wildfire activity, science, 313, 940-943, 2006.

Westerling, A. L.: Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring, Philosophical Transactions of the Royal Society B: Biological Sciences, 371, 20150178, 2016.

Wotton, B., Martell, D., and Logan, K.: Climate change and people-caused forest fire occurrence in Ontario, Climatic Change, 60, 275-295, 2003.

Yue, X., Mickley, L. J., Logan, J. A., and Kaplan, J. O.: Ensemble projections of wildfire activity and carbonaceous aerosol concentrations over the western United States in the mid-21st century, Atmospheric Environment, 77, 767-780, 2013.

Yue, X., Mickley, L. J., and Logan, J. A.: Projection of wildfire activity in southern California in the mid-twenty-first century, Climate dynamics, 43, 1973-1991, 2014.

https://doi.org/10.5194/acp-2020-80
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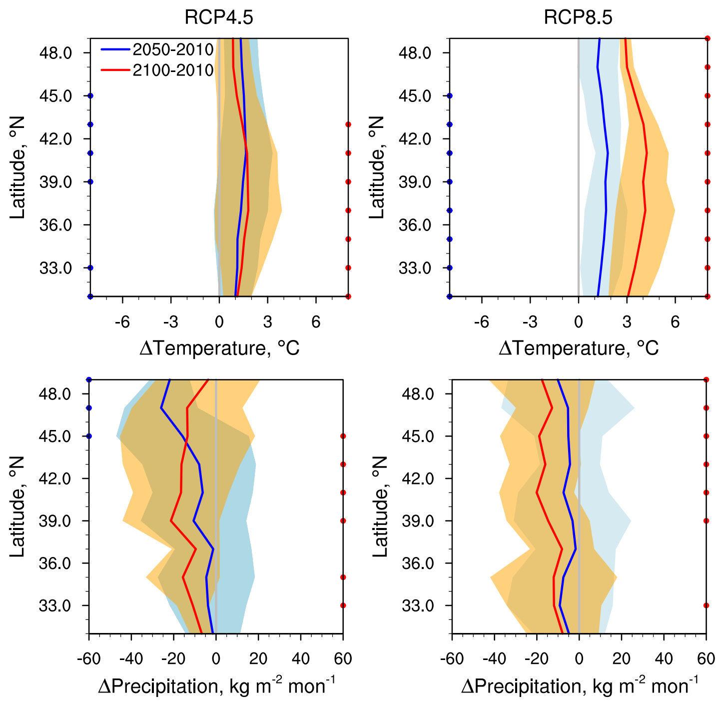
515 **Figures and tables**



516

517 **Figure 1.** Modeled changes in temperature (top) and precipitation (bottom) in July-August-
518 September (JAS) at ~2050 and ~2100 as a function of latitude over the WUS for RCP4.5 (left)
519 and RCP8.5 (right). Changes are zonally averaged and relative to the present day (~2010), with
520 5-year averages in each time slice. The bold blue lines show the changes between 2010 and
521 2050, averaged over all longitudes in the WUS (31°N – 49°N, 100°W – 125°W); bold red lines
522 show the mean changes between 2010 and 2100. Light blue and orange shadings represent the
523 temporal standard deviation across the 15 months (5 years x 3 months) of each time slice. Blue
524 dots along the axes mark those latitudes showing statistically significant differences between the
525 JAS 2010 and 2050 time slices ($p < 0.05$); red dots mark those latitudes with statistically
526 significant differences at 2100. Temperatures and precipitations are from the GISS-E2-R climate
527 model.

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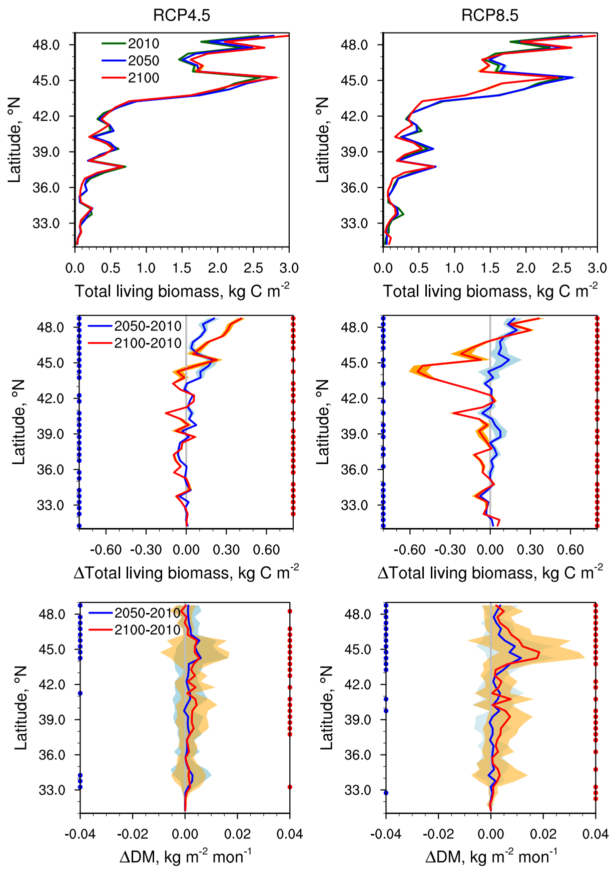

Figure 2. The top panel shows total living biomass at ~2010, ~2050 and ~2100 as a function of latitude over the WUS for RCP4.5 (left) and RCP8.5 (right), with 5-year averages in each time slice. The lower four panels are as in Figure 1, but for changes in total living biomass (middle) and lightning-caused dry matter burned (DM; bottom) as a function of latitude over the WUS. Results of living biomass and DM are from LPJ-LMfire. As in Figure 1, dots along the axes mark those latitudes showing statistically significant differences.

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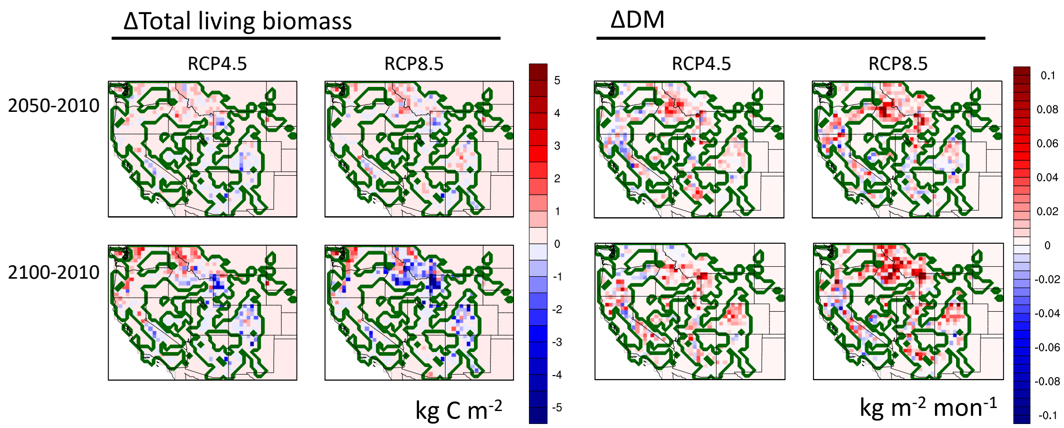

538 **Figure 3.** Simulated changes in yearly mean total living biomass and monthly mean DM averaged over the fire season in the National Forests across the WUS for the RCP4.5 and RCP8.5 scenarios. The top row shows changes between the present day and 2050, and the bottom row shows changes between the present day and 2100. Results are from LPJ-LMfire, with five years representing each time period. The fire season is July, August, and September.

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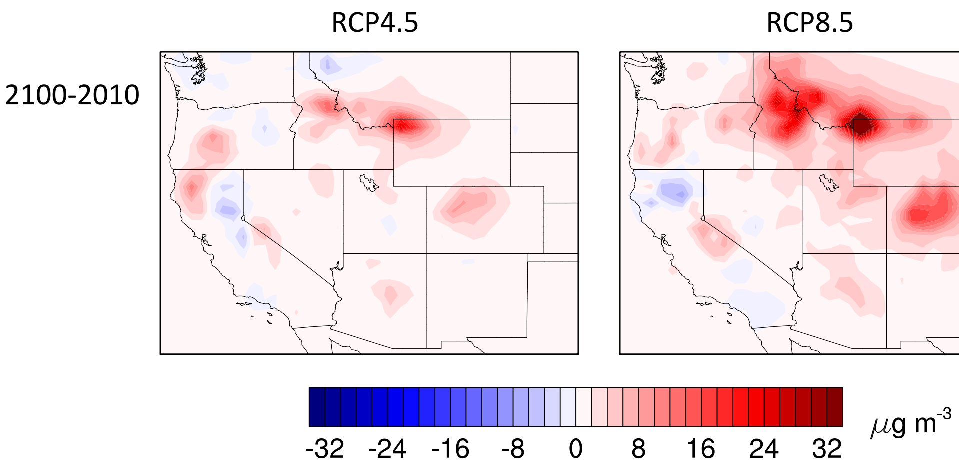

Figure 4. Simulated changes in fire-season smoke PM (BC+OC) at ~2100 relative to the present day for RCP4.5 and RCP8.5. Results are from GEOS-Chem at a spatial resolution 0.5° x 0.625°, averaged over July, August, and September. Each time period is represented by a 5-year time slice.

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Table 1. Total living biomass and dry matter burned (DM) over National Forests and Parks in the WUS and smoke PM (BC+OC) concentrations averaged across the entire West. Also shown is DM summed over National Forests in the Sierra Nevada (SN). Values for the present day (~2010) are shown in the top row; changes in ~2050 and ~2100 relative to the present day are shown in bottom two rows. Statistically significant changes are in boldface.

Time slices	**Living biomass[b], Tg/yr**		**DM[b], Tg/JAS**		**DM in SN[b], Tg/JAS**		**BC+OC[c], $\mu g\ m^{-3}$**	
	RCP4.5	**RCP8.5**	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
2010[a]	3074.8±33.7	3036.9±55.5	22.16±4.16	30.96±7.15	1.27±1.08	1.24±0.48	2.11±0.48	2.55±0.81
2050-2010[a]	138.2±46.0	126.2±80.2	**18.0±16.1**	**26.7±14.8**	0.22±1.42	0.54±1.50	--	--
2100-2010[a]	119.6±34.4	-270.7±76.1	**24.6±13.2**	**50.0±18.0**	0.91±2.10	**1.00±0.86**	**1.11±1.02**	**2.78±1.73**

[a] Each time slice represents 5 years; [b] Values are fire-season summations over National Parks and Forests;
[c] BC+OC concentrations are fire-season averages over the West;
Statistical significance is not calculated for living biomass.

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Table 2. Reclassification of LPJ-LMfire PFTs.

LPJ-LMfire (9 pfts)	**GEOS-Chem (6 pfts)**
Tropical broadleaf evergreen	Tropical forest
Tropical broadleaf raingreen	Tropical forest
Temperate needleleaf evergreen	Temperate forest
Temperate broadleaf evergreen	Temperate forest
Temperate broadleaf summergreen	Temperate forest
Boreal needleleaf evergreen	Boreal forest
Boreal summergreen	Boreal forest
C_3 grass	Crop, pasture
C_4 grass	*50%* -> savanna, grassland, shrubland; 50% -> crop, pasture