Supplementary material

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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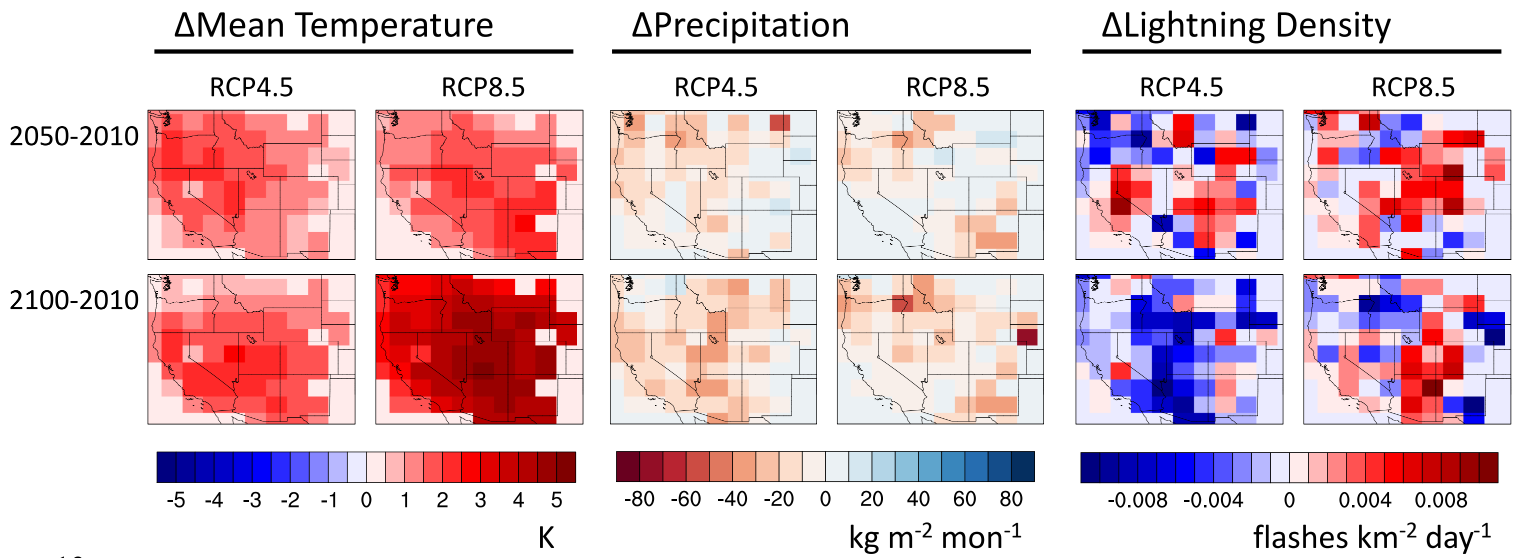

Fig. S1. Changes in monthly mean temperature, precipitation and lightning density averaged over the fire season in the western U.S. for the RCP4.5 and RCP8.5 scenarios. The top row shows changes between the present day and 2050, and the bottom row shows changes between the present day and 2100. Temperature and precipitation are from GISS-E2-R for the RCP4.5 and RCP8.5 scenarios, with five years representing each time period. Lightning density is calculated using the GISS convective mass flux following the empirical parameterization of *Magi* [2015]. The fire season is July, August, and September.

Evaluation of LPJ-LMfire fire emissions

We first evaluate the lightning-caused wildfire emissions from LPJ-LMfire over the National Forests in the western U.S. by comparing with the Global Fire Emissions Database (GFED4s) emissions over the same regions (Fig. S2). Lighting is the dominant fire source over the western U.S. forests, allowing a reasonable comparison between the two emission inventories over the forest areas in the West. The total fire-season dry matter burned (DM) over National Forests and Parks from LPJ-LMfire is 22.11 Tg for July-August-September (JAS), comparable to that from GFED4s (19.89 Tg), providing confidence in the LPJ-LMfire representation of fires without active suppression. GFED4s shows greater DM over northern Washington, Idaho, and northern California than LPJ-LMfire but overall the spatial mismatches are not large.

We then validate the carbonaceous fine particulate matter ($PM_{2.5}$; BC+OC) generated by GEOS-Chem in a simulation with the combined emissions (LPJ-LMfire over the National Forests and Parks and GFED4s elsewhere) during JAS. Simulated BC and OC also include contributions from non-fire sources, such as fossil fuel combustion from transportation, industry, and power plants. We compare the GEOS-Chem results against ground-based measurements from the Interagency Monitoring of Protected Visual Environments (IMPROVE) network in the western U.S. We find that GEOS-Chem generally reproduces the IMPROVE observations, with elevated concentrations (~3.0-5.0 $\mu g\ m^{-3}$) over the northern states and in California (Fig. S3). In JAS, large amounts of smoke PM are transported from Canada, as implied by some IMPROVE observations in Idaho and Montana. GFED4s includes the smoke from these Canadian fires, as reflected by elevated smoke PM in the northeast corner of the domain in the GEOS-Chem results. Results in RCP8.5 for the present-day are similar to those under RCP4.5 (not shown). We also compare 5-year fire-season averages of smoke PM in each grid cell in the western U.S. from GEOS-Chem against those from IMPROVE observations (Fig. S4). The GEOS-Chem simulation with combined emissions generally reproduces smoke PM within an uncertainty of 50%.

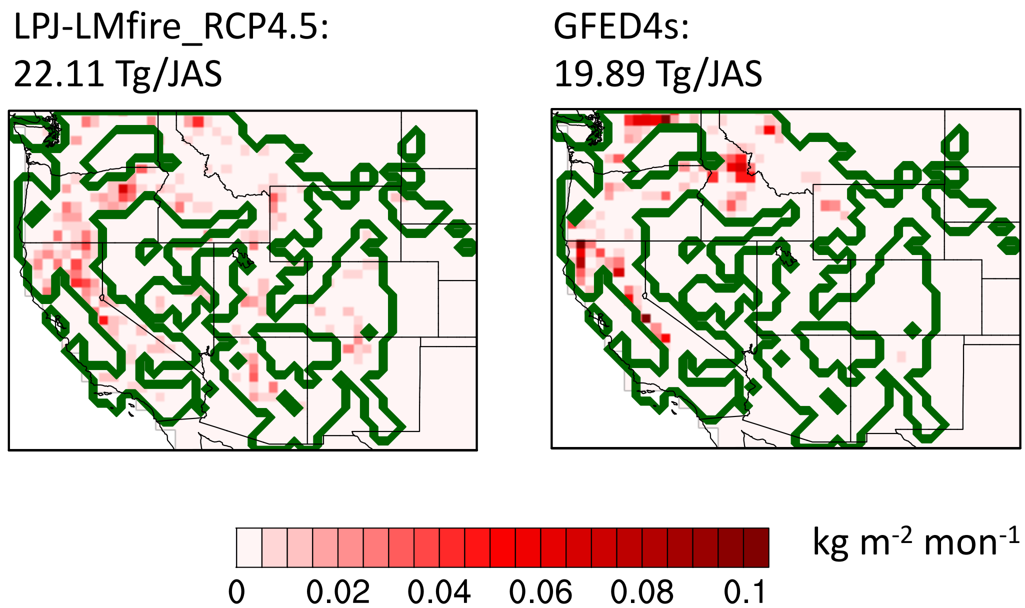

Fig. S2. Present-day (2011-2015) fire-season averaged lightning-caused dry matter burned (DM) over National Forests and Parks in the West for LPJ RCP4.5 and GFED4s. Bold green lines mark the boundaries of National Forests and Parks. Value are the total fire-season DM over the National Forests and Parks in the two inventories. The fire season is July, August, and September.

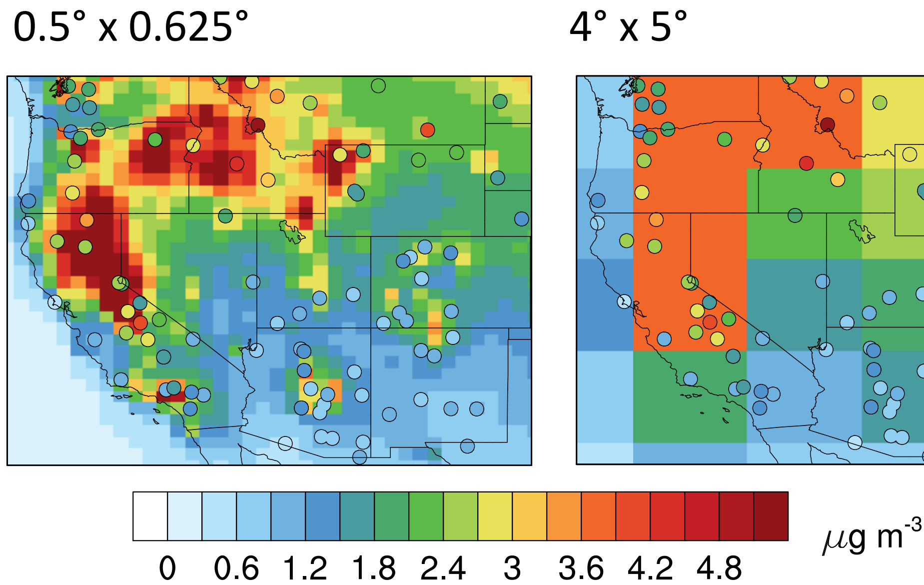

Fig. S3. Fire-season averaged smoke PM. Circles represent ground-based observations from the IMPROVE network. The colored background is from GEOS-Chem simulations at 0.5° x 0.625° and 4° x 5° spatial resolutions for the present-day (2011-2015) using the combined fire emissions from LPJ-LMfire over National Forests and Parks (within green boundaries in Fig. S2) and GFED4s over other regions. The fire season is July, August, and September.

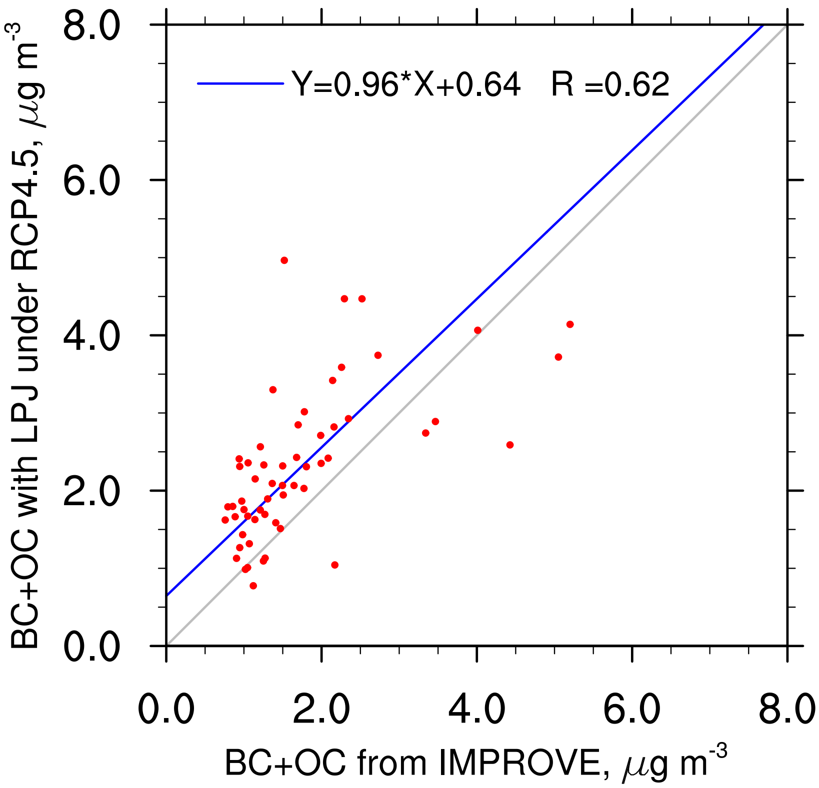

Fig. S4. BC+OC concentrations simulated with the present-day combined fire emissions from LPJ RCP4.5 (over National Forests) and GFED4s (over other regions) compared to those from IMPROVE observations. Each dot represents the 5-year fire-season average of concentrations in each grid square (with the resolution of 4° x 5°) across the western U.S. The blue line is the fitted line using reduced major axis (RMA) regression between the GEOS-Chem simulations and those from IMPROVE. The grey line denotes the 1:1 line.

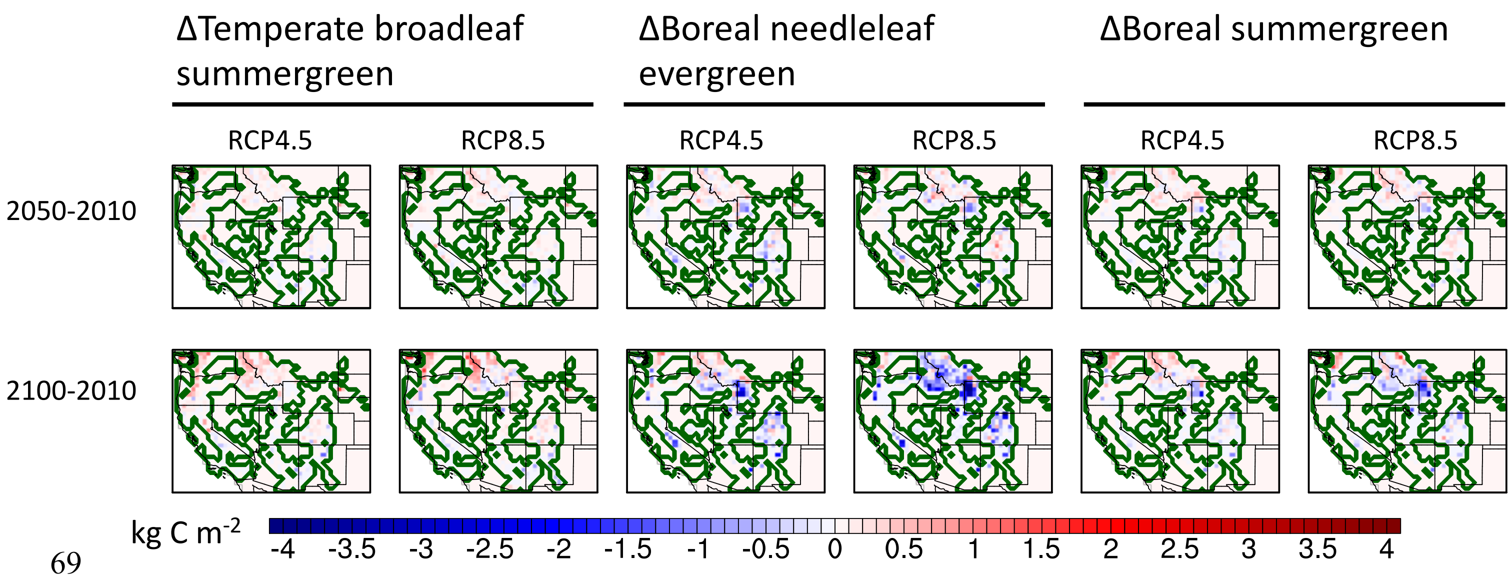

Fig. S5. Simulated changes in living biomass for the three most dominant plant functional types over the National Forests in the western U.S. for the RCP4.5 and RCP8.5 scenarios. The top row shows changes between the present day and 2050, and the bottom row shows changes between the present day and 2100. Results are from LPJ-LMfire, with five years representing each time period. The fire season is July, August, and September.

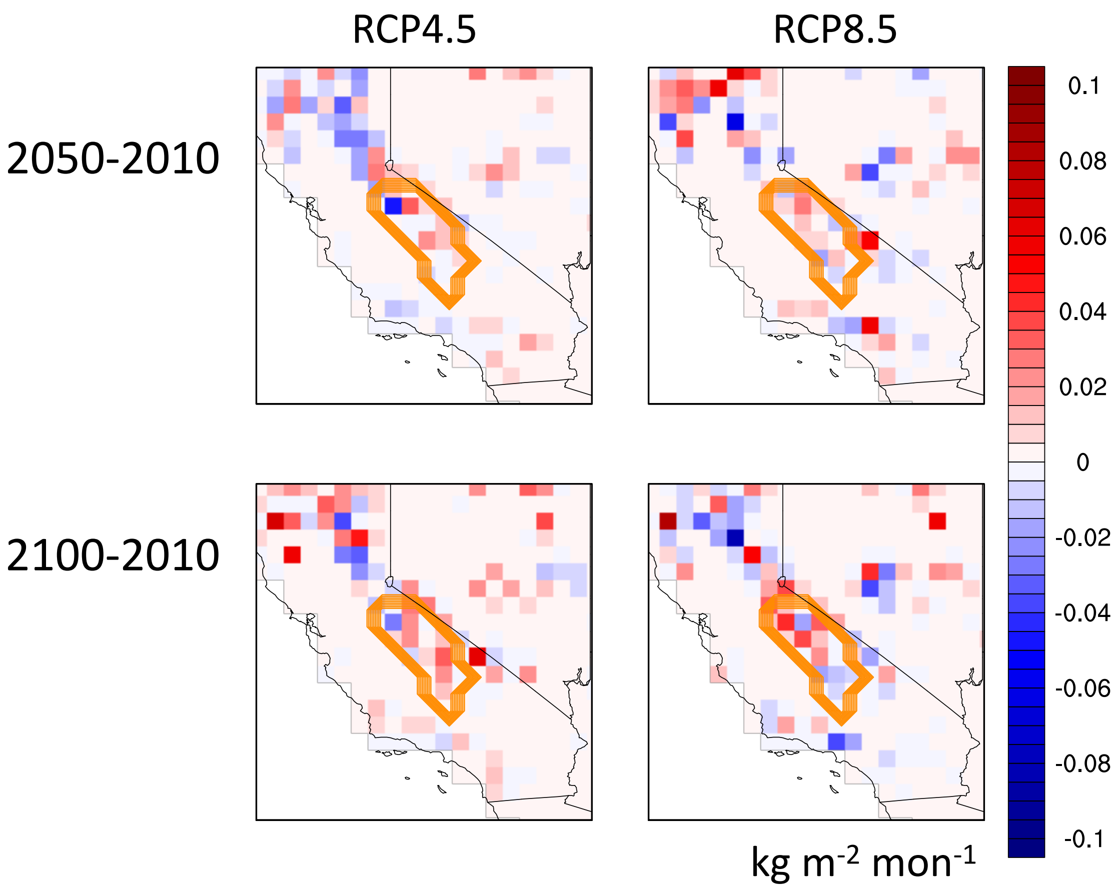

Fig. S6. Simulated changes in monthly mean lightning-caused DM averaged over the fire season over National Forests in California for the RCP4.5 and RCP8.5 scenarios. The top row shows changes in DM between the present day and 2050, and the bottom row shows changes between the present day and 2100. Results are from LPJ-LMfire for the RCP4.5 and RCP8.5 scenarios, with five years representing each time period. The fire season is July, August, and September. Bold orange lines mark the boundaries of the Sierra Nevada (SN).

Table S1. Comparison of fire predictions in the U.S. under future climate.

Methods	Region, scenarios, and future time slice	Fire metric and percent increase relative to present day	Smoke PM and percent increase relative to present day	Reference
Statistical models for lightning fires	Entire U.S. Doubled CO_2 climate	Number of fires: 44% Area burned: 78%		Price and Rind, 1994
Two climate models	Entire U.S. Doubled CO_2 climate ~2060	Seasonal fire severity rating: 10-50%		Flannigan et al., 2000
Statistical model	California, U.S. A2 ~2100	Large fire risk: 12-53%		Westerling and Bryant, 2008
Statistical models and GEOS-Chem	Western U.S. A1B ~2050	Area burned: 54% Smoke emission: 100%	Smoke PM concentrations BC: 20% OC: 40%	Spracklen et al., 2009
Climate model with global-scale fire parameterization	Global B1, A1B, A2 ~2100	Fire occurrence in the western U.S. B1: 120% A1B: 233% A2: 242%		Pechony and Shindell, 2010
MAPSS-CENTURY 1 dynamic general vegetation model	U.S. Pacific Northwest A2 ~2100	Area burned: 76-310% Burn severity: 29-41%		Rogers et al., 2011
Statistical models + GEOS-Chem	Western U.S. A1B ~2050	Area burned: 63-169% Smoke PM emissions: 150-170%	Smoke PM concentrations: 43-55%	Yue et al., 2013
Statistical models	California, U.S. A1B ~2050	Area burned: 10-100%		Yue et al., 2014
Coupled Community Land Model (CLMv4) and Community Earth System Model (CESM) [2]	Western U.S. RCP4.5 and RCP8.5 ~2050	Smoke PM emissions: • RCP4.5: 100% • RCP8.5: 50%	Total $PM_{2.5}$ concentrations[1] • RCP4.5: 22% • RCP8.5: 63%	Val Martin et al., 2015

CLMv4.5-BGC with fire parameterization coupled with CESM[3]	Contiguous U.S. RCP4.5 and RCP8.5 ~2050 and ~2100 Relative to the present day (1995-2005)	Area burned by 2050: • RCP4.5: 67% • RCP8.5: 50% by 2100: • RCP4.5: 58% • RCP8.5: 108%	Total $PM_{2.5}$ concentrations[1] by 2050: • RCP4.5: 146% • RCP8.5: 85% by 2100: • RCP4.5: 108% • RCP8.5: 246%	Pierce et al., 2017
CLMv4.5 with fire parameterization coupled with CESM[3]	Contiguous U.S. RCP4.5 & RCP8.5 ~2050 and ~2100 Relative to the present day (2000-2010)	Smoke PM emissions by 2050: • RCP4.5: 126% • RCP8.5: 54% by 2100: • RCP4.5: 125% • RCP8.5: 149% by 2050 over the West: • RCP4.5: 45% • RCP8.5: 40%	Total $PM_{2.5}$ concentrations[1] by 2050: • RCP4.5: 113% • RCP8.5: 27% by 2100: • RCP4.5: 93% • RCP8.5: 127%	Ford et al., 2018
LPJ-LMfire coupled with GEOS-Chem	Western U.S. RCP4.5 and RCP8.5 ~2050 and ~2100 Relative to the present day (2011-2015)	Smoke PM emissions by 2050: • RCP4.5: 81% • RCP8.5: 86% by 2100: • RCP4.5: 111% • RCP8.5: 161%	Smoke PM concentrations by 2100: • RCP4.5: 53% • RCP8.5: 109%	This study

[1] Total $PM_{2.5}$ is the combination of sulfate, ammonium nitrate, secondary organic aerosols, fine dust, fine sea salt, BC and OC.

[2] This model considers changes in climate, anthropogenic emissions, land cover, and land use.

[3] This model considers changes in climate, anthropogenic emissions, land cover, land use, and population.

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