Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States

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Abstract.

We investigate the impact of climate change on wildfire activity and carbonaceous aerosol concentrations in the western United States. We regress observed area burned onto observed meteorological fields and fire indices from the Canadian Fire Weather Index system and find that May-October mean temperature and fuel moisture explain 24-57% of the variance in annual area burned in this region. Applying meteorological fields calculated by a general circulation model (GCM) to our regression model, we show that increases in temperature cause annual mean area burned in the western United States to increase by 54% by the 2050s relative to the present-day. Changes in area burned are ecosystem dependent, with the forests of the Pacific Northwest and Rocky Mountains experiencing the greatest increases of 78% and 175% respectively. Increased area burned results in near doubling of wildfire carbonaceous aerosol emissions by mid-century. Using a chemical transport model driven by meteorology from the same GCM, we calculate that climate change will increase summertime organic carbon (OC) aerosol concentrations over the western United States by 40% and elemental carbon (EC) concentrations by 20% from 2000 to 2050. Most of this increase (75% for OC, 95% for EC) is caused by larger wildfire emissions with the rest caused by changes in meteorology and for OC by increased monoterpene emissions in a warmer climate. Such an increase in carbonaceous aerosol would have important consequences for western U.S. air quality and visibility.

1. Introduction

Emissions from wildfires in North America can have important consequences for air quality both regionally [*McMeeking et al.*, 2005, 2006; *McKenzie et al.*, 2006; *Spracklen et al.*, 2007; *Jaffe et al.*, 2008] and at sites thousands of kilometers from the fire [*Wotowa and Trainer*, 2000; *DeBell et al.*, 2004; *Jaffe et al.*, 2004; *Lapina et al.*, 2006; *Val Martin et al.*, 2006; *Duck et al.*, 2007; *Lewis et al.*, 2007]. Because wildfire activity in North America is largely controlled by temperature and precipitation [e.g., *Balling et al.*, 1992; *Gedalof et al.*, 2005] climate change has the potential to influence the frequency, severity, and extent of wildfires [e.g., *Flannigan et al.*, 2005]. In this study we use stepwise linear regression to evaluate relationships between the area burned by wildfires and variables chosen from observed meteorology and standard fire indices. We apply these relationships to meteorological fields calculated by a general circulation model (GCM) for 2000-2050 to determine the effect of changing climate on future area burned. Finally we use a global chemistry model, driven by the GCM, to assess the impact of wildfires in a future climate on carbonaceous aerosols in the western United States.

Records of wildfire show increasing area burned in Canada [*Stocks et al.*, 2003; *Gillett et al.*, 2004; *Kasischke and Turetsky*, 2006], Alaska [*Kasischke and Turetsky*, 2006] and the western United States [*Westerling et al.*, 2006] over the past few decades. In the western United States annual average forest wildfire area burned during 1987 to 2003 was more than six times that during 1970 to 1986 [*Westerling et al.*, 2006]. In addition to climate, wildfire behavior is also modified by forest management and fire suppression [*Allen et al.*, 2002; *Noss et al.*, 2006], so understanding the reasons for this change is complicated by simultaneous changes in climate, land use, fire suppression and fire reporting that have occurred over this period. However, changes in climate were likely the main drivers for increases in area burned both in the western United States [*Westerling et al.*, 2006] and Canada [*Gillett et al.*, 2004; *Kasischke and Turetsky*, 2006; *Girardin*, 2007]. Increases in forest wildfires in the western United States have been driven largely by earlier spring snowmelt and increasing spring and summertime temperatures; mean March-August temperatures for 1987-2003 were 0.87 K warmer than those in 1970-1986 [*Westerling et al.*, 2006].

Several studies have estimated the impacts of future climate change on wildfire. *Flannigan and Van Wagner* [1991] used three different GCMs to predict on average a 46% increase in seasonal severity rating (SSR, a measure of fire weather) across Canada under a 2 x CO_2 scenario. Similar results were found by *Flannigan et al.* [2000] who used two GCMs to predict a 10-50% increase in SSR across much of North America under the same scenario. Longer future fire seasons in Canada were predicted by *Stocks et al.* [1998] and *Wotton and Flannigan* [1993]. Increased future fire danger has also been predicted for Russia [*Stocks et al.*, 1998], the western United States [*Brown et al.*, 2004; *Westerling and Bryant*, 2008] and the European Mediterranean area [*Moriondo et al.*, 2006]. *Westerling and Bryant* [2008] predict a 10-35% increase in large fire risk by mid-century in California and Nevada, depending on the greenhouse gas emissions scenario and GCM used. Large regional variation in future wildfires are predicted by Regional Climate Models (RCMs), including decreased fire danger in parts of eastern Canada due to increased precipitation [*Bergeron and Flannigan*, 1995; *Flannigan et al.*, 2001].

Many of the above studies predict changes in fire indices, but estimates of emissions from fires require predictions of area burned. *Flannigan et al.* [2005] investigated relationships between climate and the areas of fires in Canada. Stepwise linear regression was used to derive the best predictors of area burned, chosen from meteorological variables (surface temperature, rainfall, wind speed and relative humidity) and calculated values of forest fuel moisture from the Canadian Fire Weather Index (FWI) System. Temperature and fuel moisture explained between 36% and 64% of the variance in monthly area burned depending on the ecosystem. The Canadian and Hadley Centre GCMs were used to predict increases in area burned of 74-118% under a 3 $\times$ CO_2 scenario. RCMs have also been used to study wildfire area burned in limited regions of Canada. For the boreal forests of Alberta, *Tymstra et al.* [2007] used an RCM to predict a 13% increase in area burned in a 2 x CO_2 scenario and a 30% increase in a 3 x CO_2 scenario. Most of these studies did not account for any future changes in ignition sources. *Price and Rind* [1994] used empirical lightning and fire models along with the Goddard Insitute for Space Studies (GISS) GCM to predict that more intense convection under a 2 x CO_2 scenario leads to increased lightning and a 78% increase in area burned in the United States.

Despite these efforts to predict the effect of future climate on wildfires, there have not been studies of the impact of these future wildfires on air quality. In this paper we predict how wildfires in the western United States will respond to changes in climate between the present day and 2050 and evaluate the impacts on aerosol air quality. We apply the technique of *Flannigan et al.* [2005] to the western United States, building regressions between observed wildfire area burned [*Westerling et al.*, 2003] and observed climate. Projections of future climate, calculated by the GISS GCM, are used to predict changes in wildfire area burned. We use the GEOS-chem chemical transport model (CTM) driven by meteorology from the GISS model to quantify the impact of changing wildfire on carbonaceous aerosol concentrations.

2. Predicting wildfire emissions for 2000-2050

Here we describe our prediction of future wildfire emissions of carbonaceous aerosol in the western United States, defined as the domain 31°-49°N, 125°-100°W (from the Pacific Coast to eastern Colarado and from the Mexican border to the Canadian border).

2.1. Area Burned Predictions

We extend the approach of *Flannigan et al.* [2005] to the western United States, building regressions of observed area burned with surface meteorological data and output from the FWI model. Observed area burned was taken from the database of *Westerling et al.* [2003]. They used reports from various agencies in the United States that provided the area burned on federal land, and the start and end date of individual fires, from 1980 to 2000. This database has been extended to 2004. *Westerling et al.* [2003] assumed that the fires burn entirely in the month during they started (end dates are often unreliable), and the areas were aggregated on a grid of 1° x 1°. Because the gridded database used only the start date of each fire, it may not accurately reflect the seasonal dependence of each fire season. In addition, the wildfire timeseries is relatively short, and if there are only a few extreme events, it is difficult to fit with the least squares approach used here. For these reasons we chose to predict annual area burned.

Area burned was binned according to the ecological stratification of *Bailey et al.* [1994]. This system defines 18 ecosystem classes in the western United States. These ecosystems were further aggregated to produce 6 ecoregions with similar vegetation and climate, as shown in Fig. 1. We tested our regressions with the original 18 ecosystems, but found we could better fit area burned for the larger ecoregions, as did *Flannigan et al.* [2005] for Canada. This is probably caused by meteorological factors that influence area burned operating at synoptic scales, and larger spatial units providing some statistical smoothing of noisy data for area burned. We use these 6 ecoregions (Pacific North West, California Coastal Shrub, Desert South West, Nevada Mountains/Semi-desert, Rocky Mountains Forest and Eastern Rocky Mountains/ Great Plains) for the rest of this work.

We obtained from the USDA Forest Service, data for four meteorological variables important to wildfire frequency and required as input to the FWI model: daily 12.00 local standard time temperature, relative humidity, wind speed and 24-hour accumulated rainfall [available at http://fam.nwcg.gov/fam-web/weatherfirecd/]. Meteorological stations were selected if they reported data for at least two-thirds of the 1980-2004 time period and if the altitude of the station was within 500 m of the mean altitude of all stations within that ecoregion. Table 1 shows the number of stations selected for each ecoregion. Temperature and relative humidity values at each station were adjusted to the mean elevation of the stations. For temperature the adjustment is based on the U.S. Standard Atmosphere lapse rate of -6.5 K/km. Relative humidity was then recalculated using the adjusted temperature. For 1980-2004 we calculated a daily value for each meteorological variable and each ecoregion as an average across the selected meteorological stations.

The calculated daily values of the four meteorological variables were used as input to the Canadian FWI System [*Van Wagner*, 1987]. The model calculates daily fuel moisture codes and fire severity indices using these four variables to track changes in forest fuel moisture. A schematic of this model is shown in Fig. 2. The fuel moisture codes describe the moisture content of three distinct fuel layers in the forest floor. The Fine Fuel Moisture Code (FFMC) represents surface fuel litter and changes rapidly with short-term changes in atmospheric moisture (time lag of 2/3 day). The Duff Moisture Code (DMC) represents loosely compacted organic layers (time lag of 15 days) and the Drought Code (DC) represents deep layers of compacted fuel and reacts to seasonal droughts (time lag of 52 days). The fire severity ratings combine information from the fuel moisture codes to give an indication of the fire danger or rate of fire spread. The Build-up Index (BUI) combines DMC and DC and is an indication of the availability of fuel for consumption. The potential rate of spread of a fire is calculated by combining wind speed and FFMC to give the Initial Spread Index (ISI). The ISI and BUI are combined to give the Fire Weather Index (FWI) which is a rating of fire intensity. The Drought Severity Rating (DSR) is an exponential function of the FWI and gives an indication of the difficulty of fire control.

Linear forward stepwise regression was used for each of the six ecoregions with annual area burned as the predictand. For predictors we used the maximum and mean of the daily May to October values of temperature, relative humidity and wind speed and the 7 output fields from the FWI model (described above). In addition we used May to October mean daily rainfall and total May to October rainfall. This gives 22 potential predictors. We used the same test for significance as *Flannigan et al.* [2005]; terms were accepted only if they met a significance level (p value) of 0.15. The predictor with the highest correlation coefficient was added to the regression first. Predictors were then added in the order that maximised the correlation coefficient, until the correlation coefficient did not increase by a preselected amount (typically 2%), or until a predictor was selected that resulted in a non-physical relationship between area burned and fuel moisture. In general, 2 predictors were selected for each ecoregion. We tested our method using both area burned and natural logarithm of area burned. We found similar correlation coefficients with the two predictands. For the rest of this work prediction of linear area burned was used as this results in total predicted area burned being equal to observed area burned. This is not the case when logarithm of area burned is predicted.

Figure 3 shows a comparison of observed and predicted annual area burned in the Pacific Northwest and Rocky Mountain Forest ecoregions. The observations show large interannual variability in area burned, with a range of 7500 ha/year to 440,000 ha/year in the Pacific Northwest and 4800 ha/year to 1.45 million ha/year in the Rocky Mountain Forest. In the Pacific Northwest the regression explains 52% of this interannual variability. The chosen predictors for this region are mean drought code and mean temperature, for which the individual correlation coefficents (R^2) are 46% and 43% respectively. The greatest observed area burned occurred in 1987 and 2002 coincident with high DC and T. Predicted area burned is also maximum during these two years but is underestimated by about 40%. In the Rocky Mountain Forest the regression explains 47% of the variability in annual area burned. The best predictors for this region are mean temperature and maximum build-up index for which the individual correlation coefficents (R^2) are 42% and 40% respectively. The regression underpredicts the largest fire year in 1988 by about 60%, but other large fires years (e.g., 2000 and 2001) are well predicted.

Table 1 shows the best predictors and the explained variance for the 6 ecoregions in the western United States. The regressions explain 24-57% of variance in annual area burned.

Explained variance is generally greater in forest dominated ecosystems (48-52%) than in shrub and grass dominated ecosystems (24-49%). The lower explained variance in these ecosystems is likely due to the importance of the previous year's climate for fire activity in these areas [*Westerling et al.*, 2002; *Westerling and Bryant*, 2008; *Littell et al.*, 2008] which we do not take into account with our method. However, as we show later, these shrub and grass dominated ecosystems have limited impact on regional particulate air quality due to low fuel loads.

Best predictors of area burned are ecosystem dependent but generally include temperature and fuel moisture codes (FFMC or DC). Temperature is the most commonly chosen predictor in the western United States, as has been found previously in Canada [*Flannigan et al.*, 2005]. High temperatures are associated with clear skies, persistent stagnation, and dry fuel - conditions that favor wildfire occurrence.

2.2. Simulation of future area burned

To calculate future area burned, we archived daily mean temperature, relative humidity and local noon windspeed as well as 24-hour accumulated rainfall from the GISS simulation for 2000-2050. We used the 'q-flux' version of the GISS GCM 3 [*Rind et al.*, 2007], which has a horizontal resolution of 4° x 5° and 23 vertical sigma levels between the surface and 0.002 hPa. In the q-flux version, ocean heat transport fluxes are kept fixed while ocean temperatures and ocean ice respond to changes in climate. Observed concentrations of well-mixed greenhouse gases, ozone, and aerosols were used for the model spinup between 1950 and 2000, starting from a climate equilibrium [*Hansen*, 2002]. For 2001 to 2055 we used concentrations of well-mixed greenhouse gases from the IPCC SRES A1B scenario, with CO_2 calculated using the Bern-CC model [*Houghton*, 2001]. Under this scenario CO_2

mixing ratios reach 522 ppm by 2050. We assumed no changes in ozone or aerosols from 2001 to 2055 for the purpose of calculating climate change. This model predicts global mean July temperatures to increase by 1.8°C from 2000 to 2050.

Because the GISS GCMs tend to have a warm continental bias [*Schmidt et al.*, 2006], we scaled temperature as well as the other fields to match observations by multiplying the GISS output by the ratio of mean observed to mean GISS values in each model grid square for May to October of 1990-2000. The adjusted GISS meteorology was used as input for the FWI model to calculate daily fuel moisture parameters. The regressions developed in section 2.1 were then applied to GISS and FWI output to predict ecosystem specific annual area burned.

Fig. 4 shows the simulated changes between 2000 and 2050 in mean May through October noon values of the four meteorological variables over the western United States; we compare the means for 1996-2005 and for 2046-2055. Temperatures increase across the western United States by 1-3^{o}C, with the largest increases in the Pacific Northwest and Nevada Mountains/Semi-desert ecoregions. The projected change in temperature is large, 1.5-1.8 times the standard deviation in May-October mean temperature, even though 2049 is a relatively cold year for the western United States. Precipitation and relative humidity increase by 7% and less than 2% respectively across the western United States with the greatest increases in the Eastern Rocky Mountains/Great Plains and Desert Southwest ecoregions. Mean windspeeds are projected to decrease slightly throughout the western United States. These climate projections lie within the ensemble of climate model predictions [*Seager et al.*, 2007; *Christensen*, 2007], giving us confidence that our results are robust.

We applied the adjusted GCM meteorology to our area burned regression model to predict annual ecoregion area burned from 1996 to 2055. Table 2 shows the average observed area burned for 1980 to 2004 and average calculated area burned for a 10-year period in the present day (1996 to 2005) and in the future (2046 to 2055) for each of the 6 ecoregions. Average area burned in the present day is calculated with a normalised mean bias of +10% to -25% depending on the region. Fig. 4e shows simulated annual area burned for 1996-2005 and Fig. 4f shows the ratio of area burned in 2046-2055 to that in 1996-2005.

Total area burned across the western United States is projected to increase by 54% for 2046-2055 relative to 1996-2005. This projected increase is significant (Student's t test p=0.03). Area burned is predicted to increase in all regions except the Eastern Rocky Monutains/Great Plains where the change is not significant. Statistically significant ($p<0.05$) increases in area burned are projected for the Rocky Mountain Forest (78%), Pacific Northwest Forest (175%) and Desert Southwest (43%) ecoregions (see Table 2). In these ecoregions area burned by mid-century is predicted to increase by more than one standard deviation. We used our regression equations (Table 1) along with the predicted changes in meteorological and FWI parameters to quantify the contributions of the different predictors to the change in predicted area burned (see Table 3). Simulated increases in temperature (Fig. 4) are responsible for more than 80% of the predicted increase in area burned in these ecoregions.

For most of the West, temperature plays the main role in driving future changes in area burned. However, the small (but insignificant) reduction in area burned in the Great Plains/Eastern Rocky Mountains is due to increased precipitation simulated by the GCM. In the Nevada Mountains/Semi-desert and to a lesser extent in the Desert Southwest ecoregions the impact of increasing temperature is partly offset by increasing precipitation; there is no significant change in area burned in the former region and a 43% increase in the Desert Southwest ecoregion.

Figure 5 shows the interannual variability in predicted area burned and in the predictors used to calculate area burned in the Pacific Northwest and Rocky Mountain Forest ecoregions. Interannual variability in predicted area burned is similar to that in observed area burned. We fit the predicted trend in area burned for each ecoregion using linear regression and found that the Pacific Northwest, Desert Southwest and Rocky Mountain Forest ecoregions have significant positive trends, as shown in Table 2.

2.3. Production of wildfire emissions

To calculate emissions from wildfires, we took the following steps. We first converted annual area burned to monthly area burned by using the average observed seasonal variability of wildfire in each ecoregion in 1980-2004. We assumed that the seasonality of wildfire remains the same in the future. Calculated ecoregion area burned was mapped onto a 1°x1° grid using the observed area burned data to constrain the typical spatial extent of fires within each ecoregion. Figure 6 shows the fraction of 1°x1° grid squares that contain 70% of observed annual area burned in any one year in each of the six ecoregions. For all ecoregions, 70% of area burned in a particular year occurs in 5-25% of the ecoregion. To match this observed behavior, we place 70% of projected area burned in 10% of 1°x1° grid squares in each ecoregion. We locate these grid squares randomly within each ecoregion. The remaining 30% of area burned was averaged across the remaining 90% of grid squares within the ecoregion. To check for bias introduced by the random placement of wildfires within each ecoregion, we created a 100-member ensemble of simulations of yearly biomass consumption, each with a different randomly chosen set of wildfire locations. Our results showed only a 1% one-sigma variation in total biomass consumption over the simulation period.

Emissions of carbonaceous aerosol from wildfires were calculated using the predicted 1°x1° wildfire area burned maps, ecosystem specific fuel loadings from the USDA Forest Service [*McKenzie et al.*, 2007] and emission factors from *Andreae and Merlet* [2001]. The fuel loadings are available on a grid of 0.025°x0.025°, and we formed an area weighted mean for each 1°x1° grid-box. We assume wildfires occur with 25% high, 25% medium and 25% low severity and that 25% of predicted area burned remains unburned, based on an analysis of the largest wildfires in 2002 in the continental United States [*Randall*, 2004]. We assume that fuel loadings and fire severity do not change between present day and 2050, so that the emissions of carbonaceous aerosol per unit area burned do not change over the simulation period.

We find that wildfires in the Pacific Northwest and Rocky Mountain Forest ecoregions dominate present day biomass consumption by fires in the western United States, accounting for 30% and 43% respectively of the total consumption for 1980-2004 using the observed area burned from *Westerling et al.* [2003] with updates (see Table 4). Wildfire in these two ecoregions will therefore have the largest potential impact on regional air quality. The Nevada Mountains/Semi-desert ecoregion has the greatest area burned, 35% of the total for 1980-2004 (Table 2), but accounts for only 7% of the total biomass consumption because of low fuel loads. Similarly, the Californian Coastal Shrub and Desert Southwest with 16% of area burned account for only 6% of total biomass consumption.

Figure 7 contrasts the different spatial distributions of area burned and fuel consumption in the western United States.

The calculated annual mean dry biomass consumption based on observed area burned is 14.2 Tg for 1980-2004. Predicted mean dry biomass consumption in the western United States, averaged over the 100-member ensemble of simulations, increases from ∼13.8 Tg/year for 1996-2005 to ∼26.4 Tg/year for 2046-2055, an increase of ∼90% (see Table 4). This increase is statistically significant ($p<0.01$). The linear trend in biomass consumption is 0.23±0.07 Tg year^{-1}. Figure 8 shows the trend in predicted dry biomass consumption by wildfire in the western United States for 1996-2055 plotted as the standardized daparture from the mean for 1996-2005 (Standardized departure$_i$ $= [P_i - \bar{P}_{(1996-2005)}]$/standard deviation($P_{1996-2005}$), where P_i is the biomass consumption in year i). A low fire year in 2046-2055 (except for 2049) is about 1 standard deviation above the 1996-2005 mean and is equivalent to a high fire year during 1996-2005.

3. Simulations of atmospheric EC and OC

We use our simulated wildfire emissions along with a global chemistry model to calculate the changes in aerosol air quality over the western United States.

3.1. Model Description

We predict atmospheric carbonaceous aerosol concentrations using the GEOS-Chem global 3-D model of tropospheric chemistry [*Bey et al.*, 2001; *Park et al.*, 2003] driven by meteorological fields from the NASA/GISS GCM. The interface between the GEOS-Chem CTM and the GISS GCM is described in *Wu et al.* [2007a, b] and validated for gas phase species by *Wu et al.* [2007a] and for aerosols by *Liao et al.* [2007]. We described the GISS model version used in this work in section 2.2.

Meteorological output from the GISS GCM was archived with 6-hour resolution (3 hours for surface quantities and mixing depths) and used as input to the CTM. We used GEOS-Chem model version v7.04 (see http://www-as.harvard.edu/chemistry/trop/geos) with the same spatial resolution as the GCM, 4°x5°.

The model treats EC and OC with a hydrophobic and hydrophilic fraction for each (giving 4 advected tracers). Combustion sources emit hydrophobic aerosol which become hydrophilic with an e-folding time of 1.2 days [*Cooke et al.*, 1999; *Chin et al.*, 2002]. We assumed that 80% of EC and 50% of OC emitted from primary sources are hydrophobic [*Cooke et al.*, 1999; *Chin et al.*, 2002; *Chung and Seinfeld*, 2002]. Anthropogenic emissions of OC over the United States are from *Cooke et al.* [1999] with the correction factor from *Park et al.* [2003]. Biofuel OC emissions are from *Yevich and Logan* [2003] and from *Park et al.* [2003] for the United States. In the western United States, we used fire emissions calculated as described in section 2.3, using one member of the ensemble of simulations with random placement of fires within each ecoregion. Outside of the western United States we used climatological biomass burning emissions derived from *Lobert et al.* [1999] with seasonality from *Duncan et al.* [2003]. Biomass burning emissions were emitted into the boundary layer. Emissions of monoterpenes were calculated using *Guenther et al.* [1995] and vary according to temperature and solar radiation. We did not account for the effects of changing CO_2 concentrations [e.g., *Constable et al.*, 1999] or changing land cover [*Sanderson et al.*, 2003] on monoterpene emissions from vegetation. We assumed a 10% carbon yield of hydrophilic OC from terpenes [*Chin et al.*, 2002]. A global evaluation of GEOS-chem EC and OC is given by *Chin et al.* [2002], and a more detailed evaluation over the United States can be found in *Park et al.* [2003].

3.2. Impact of future wildfires on carbonaceous aerosol concentrations

The short lifetime of EC and OC results in concentrations over the western United States being dominated by local emissions. In *Spracklen et al.* [2007] we showed that interannual variability in western United States wildfire emissions controls much of the observed interannual variability in summertime atmospheric OC concentrations. *Park et al.* [2003] showed that trans-Pacific transport from natural and anthropogenic Asian sources contributes only 2% of the United States OC burden. Here we make a first prediction of the impacts of climate change on future carbonaceous aerosol concentrations in the western United States resulting from a change in the area of western United States fires, assuming that wildfires outside the western United States remain constant. To isolate the impacts of changes in fires resulting from changes in climate, we maintained anthropogenic emissions of EC and OC from fossil fuel and biofuel sources at their present day values.

We performed two 5-year simulations for the present-day (1996-2000) and for the mid-21st century (2046-2050). Each model run was initialized with a one-year spin-up. Figure **??** shows simulated summertime OC and EC concentrations in the western United States for these two time periods. Summertime mean concentrations of OC over the western United States increase from 1.4 μg m^{-3} to 2.1 μg m^{-3} over 50 years (an increase of 40%) whereas EC increases from 0.18 μg m^{-3} to 0.21 μg m^{-3} (18%). The smaller fractional increase in EC concentrations is a result of EC in the western United States being more dominated by fossil fuel emissions than is OC [*Spracklen et al.*, 2007]. The maximum increase in carbonaceous aerosol concentrations occurs over the north-west United States (Oregon, Washington, Idaho, western Montana and northern California) where absolute OC increases 1-4 μg m^{-3}(15-70%) and EC aerosol increases 0.05-0.2 μg m^{-3} (10-70%). These large increases in carbonaceous aerosol are caused by the large increase in area burned simulated for the Pacific Northwest and Rocky Mountain Forest ecoregions (Table 2). The smaller increases in carbonaceous aerosol in the southwest (southern California, Arizona, New Mexico) reflect the smaller predicted increases in wildfires in these areas.

To separate the impact of direct changes in wildfire emissions from the impact of changing climate on emissions of monoterpenes and on aerosol removal and transport, we performed two sensitivity studies: one with present-day climate and future wildfire activity and one with future climate and present-day wildfire activity. Figure 10 summarizes the results for the western United States (31°-49°N, 125°-100°W) for these scenarios and for the standard present-day and future simulations described above. The effect of a cold future summer (year 4) shows up clearly as a year with low regionally averaged concentrations of both OC and EC aerosol. Future wildfire emissions and future climate drive an 18% increase in EC concentrations and a 40% increase in OC concentrations relative to present day across the western United States (see above). Future wildfire emissions, but present-day climate, result in EC concentration increasing by 17% and OC concentrations by 30%. Increased wildfire emissions in the future are therefore responsible for the majority of the increase in carbonaceous aerosols, 75% for OC and 95% for EC.

Simulated EC concentrations in the future climate but with present-day wildfire emissions increase by only 3%. *Wu et al.* [2007b] calculated a 5% decrease in afternoon mixing depths over the Northwest in the future climate, which would increase EC concentrations.

However, this effect is offset by increasing precipitation in this region. Concentrations of OC in the future climate, but with present-day wildfires, are 14% greater than present-day. Most of this change (∼80%) is due to increasing temperature driving increased monoterpene emissions and secondary organic aerosol formation. The temperatures given by the GISS model combined with the *Guenther et al.* [1995] emissions algorithm predict a ∼20% increase in monoterpene emissions in the United States by 2050.

4. Discussion and conclusions

We have quantified for the first time the effect of changing wildfire activity in a warming climate on carbonaceous aerosol concentrations in the western United States in future decades. We used stepwise linear regression to derive relationships between observed meteorology and observed wildfire area burned for 1980-2004. Our regressions are ecosystem dependent, with temperature and fuel moisture explaining 24-57% of the variance in annual area burned. Our focus is on the prediction of wildfire in forest dominated ecosystems that contribute most substantially to carbonaceous aerosol emissions due to their greater fuel loads. Our approach works well for these ecosystems where the meteorology of the particular fire season has the dominatant control on fire, but less well for shrub and grass dominated ecosystems where fuel loads, and hence wildfire, is strongly influenced by the previous year's precipitation [*Littell et al.*, 2008].

Following the IPCC A1B greenhouse gas scenario, the GISS GCM predicts a 2 K increase in summertime temperature and a ∼7% increase in summertime precipitation by mid-century in the western United States. These predicted changes in climate increase projected area burned in the western United States in 2046-2055 by 54% relative to 1996-2005. Predicted changes to area burned vary regionally, from no change to an increase of

175%, because of regional changes in simulated climate combined with varying ecosystem response to a changing climate. The largest increases in area burned are projected for the Pacific Northwest (78%) and Rocky Mountain Forest (175%) ecoregions where wildfire appears to depend most strongly on temperature. This is consistent with the change in wildfire activity observed in the western United States over the past few decades; sixty percent of the six-fold increase in forest fire area burned that occurred between 1970-1986 and 1987-2003 was located in in the Northern Rockies, and 18% in the Sierra Nevada, Cascades and coast ranges of Oregon and California [*Westerling et al.*, 2006]. Our method projects little change in area burned by 2050 for the Nevada Mountains/Semi-desert and Eastern Rocky Mountains/Great Plains ecoregions because simulated increases in precipitation compensate for increases in temperature in these regions.

We use the GEOS-chem CTM, driven by meteorology from the GISS GCM, to predict changes in carbonaceous aerosol concentrations over the western United States. We predict that mean summertime OC concentrations in 2046-2050 increase by 40% (from 1.5 to 2.1 μg m^{-3}) and EC concentrations by 18% (from 0.18 to 0.22 μg m^{-3}) relative to 1996-2000. The largest projected increases are in the north-west United States, co-located with the greatest increases in wildfire. Most of the increase in carbonaceous aerosol concentrations (95% for EC and 75% for OC) is caused by increases in wildfire emissions, which are predicted to increase by 90%. Changes in meteorology that occur between present day and mid-century contribute about 5-10% of the predicted change in carbonaceous aerosol concentrations. For OC, the remainder of the change (20%) is caused by the predicted increase in monoterpene emissions, due to rising temperature, and the resulting increase in secondary organic aerosol formation which has been previously predicted [*Heald et al.*, 2008].

In common with previous studies of future wildfires there are limitations in this study. We did not account for changes to vegetation, ignition, the length of fire season or human activity. Future wildfires may be modified by changes in the distribution of vegetation caused either by direct anthropogenic land-use change or by climate change. In this paper, we considered a 50-year timescale over which vegetation will not change substantially, unless it is driven by wildfire [*McKenzie et al.*, 2004] or pest outbreaks [*Logan et al.*, 2003; *Hicke et al.*, 2006]. Our assumption of unchanging vegetation implies that future increases in wildfire are not limited by the availability of vegetation. Even in large fire years, less than 2% of an ecoregion typically burns, so this assumption is likely to be valid over the timescales considered here. Over longer timescales, changes to fire activity will change fire-return intervals, with potential impacts on vegetation and fuel loads [*Fellows and Goulden*, 2008]. Over these longer timescales the future distribution of vegetation may have an important impact on future wildfire emissions and air quality.

Wildfire severity may change in a changing climate, altering the burn severity and emissions of carbonaceous aerosol per unit burned area. Here we have assumed that wildfire intensity remains unchanged over the simulation period. Changes to wildfire due to changes in lightning frequency [*Price and Rind*, 1994] and change to anthropogenic ignition [*Wotton et al.*, 2003] are also not considered here. A longer wildfire season is possible in a future climate, and an earlier start to the wildfire season has been already been observed in the western United States [*Westerling et al.*, 2006]. We predict annual area burned and do not explore possible changes in the length of the fire season. Consequently, we focused on the air quality impact of wildfires in summer (June - August). This is the period of greatest wildfire activity and also the period when air quality degradation from wildfires is at its worst. However, longer wildfire seasons in the future may extend the negative impacts on air quality further into the spring and autumn.

The vertical extent of wildfire emissions is a further uncertainty in this analysis. There is evidence that some fraction of wildfire emissions are injected above the boundary layer [*Leung et al.*, 2007; *Mazzoni et al.*, 2007; *Kahn et al.*, 2007]. How this injection height will vary in the future with potential changes in fire severity and changes in atmospheric stability is also uncertain. In this study we have assumed wildfire emissions are injected into the boundary layer and we do not consider any future change.

This study has explored the role of future climate change on wildfire in the western United States. The predicted increases in wildfire have potential implications for ecology, carbon balance, land management and fire suppression in western forests. In this work we focussed on the the impacts of changing wildfire on carbonaceous aerosol concentrations. We predict summertime mean OC concentrations across the western United States to increase by 40% and EC concentrations by 20% by mid-century relative to present-day. Carbonaceous aerosol currently accounts for 40% of fine aerosol mass in the western United States [*Malm et al.*, 2004]. Assuming other aerosol components remain unchanged, carbonaceous aerosol will account for ∼50% of fine aerosol mass by mid-century. This increase will have negative impacts on atmospheric visibility and human health. Future work is required to extend this study to the boreal forests of North America and Siberia, expand the impact to other atmospheric species such as ozone and to study the potential climate feedbacks of increased wildfire [*Randerson et al.*, 2006].

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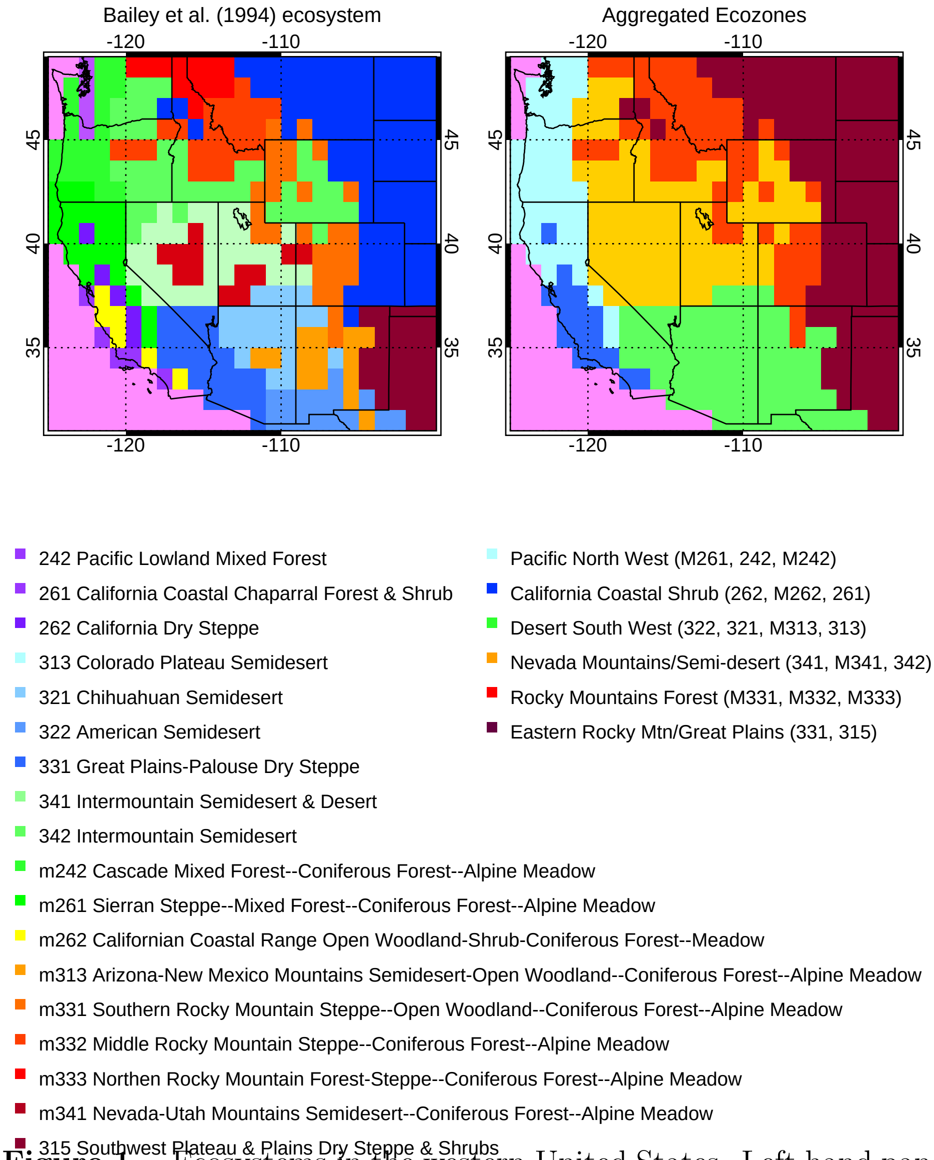


Figure 1. Ecosystems in the western United States. Left hand panel shows Bailey et al. [1994] ecosystem classes projected onto a 1° by 1° grid. Right hand panel shows aggregated ecosystems that are used in this analysis: Pacific Northwest, Californian Coastal Shrub, Desert Southwest, Nevada Mountains/Semi-desert, Rocky Mountains Forest and Eastern Rocky Mountains/Great Plains.

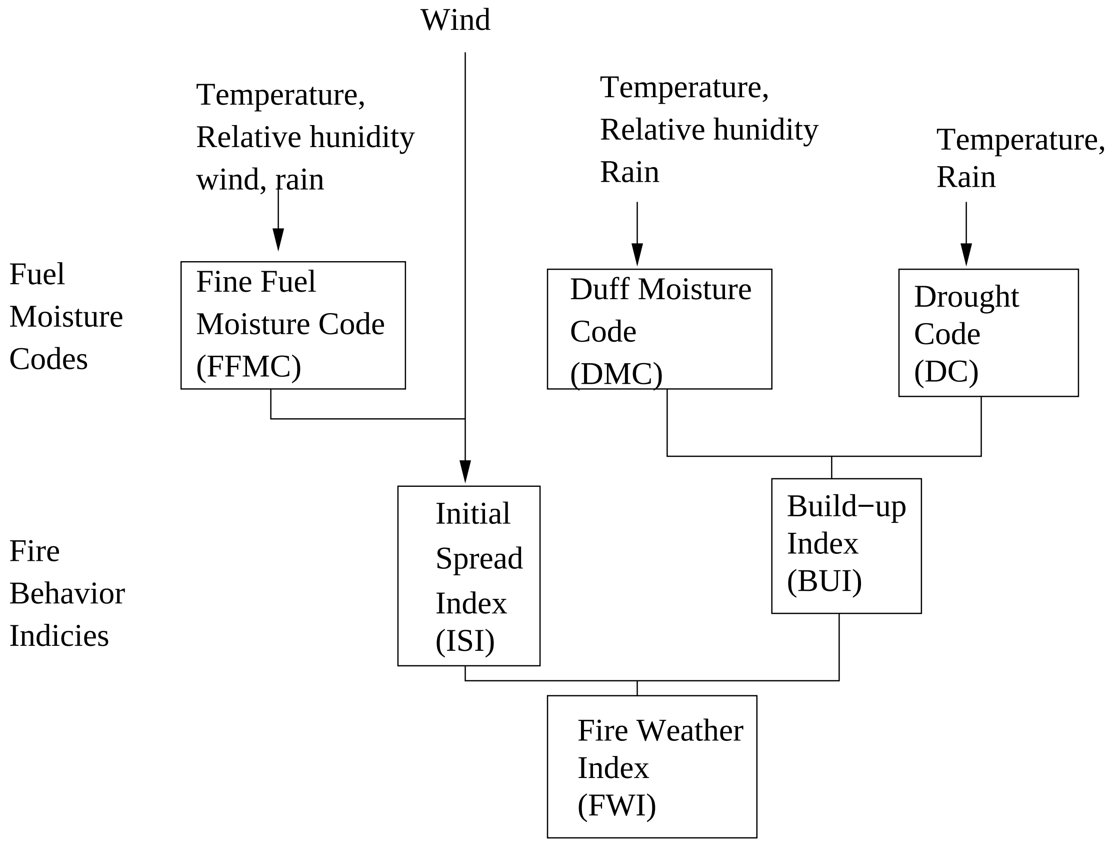


Figure 2. Schematic of the Canadian Fire Weather Index (FWI) System.

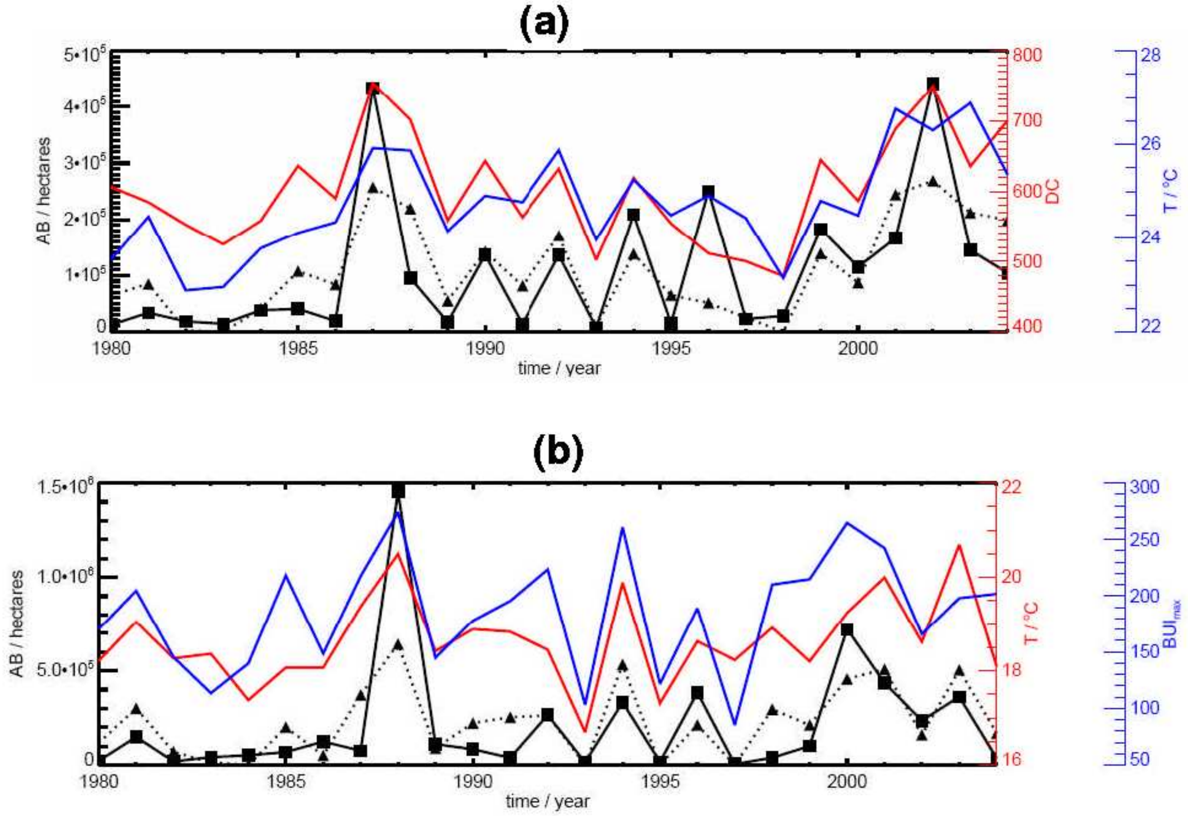


Figure 3. Annual area burned between 1980 and 2004 in (a) Pacific Northwest and (b) Rocky Mountain Forest ecoregions; Observed [*Westerling et al.*, 2003] (filled squares) and predicted using stepwise linear regression (filled triangles). Also shown are the predictors chosen by the regression (mean or maximum of the daily values for May to October): mean tempertaure (T), mean Drought Code (DC) and maximum Build-up Index (BUI_{max}).

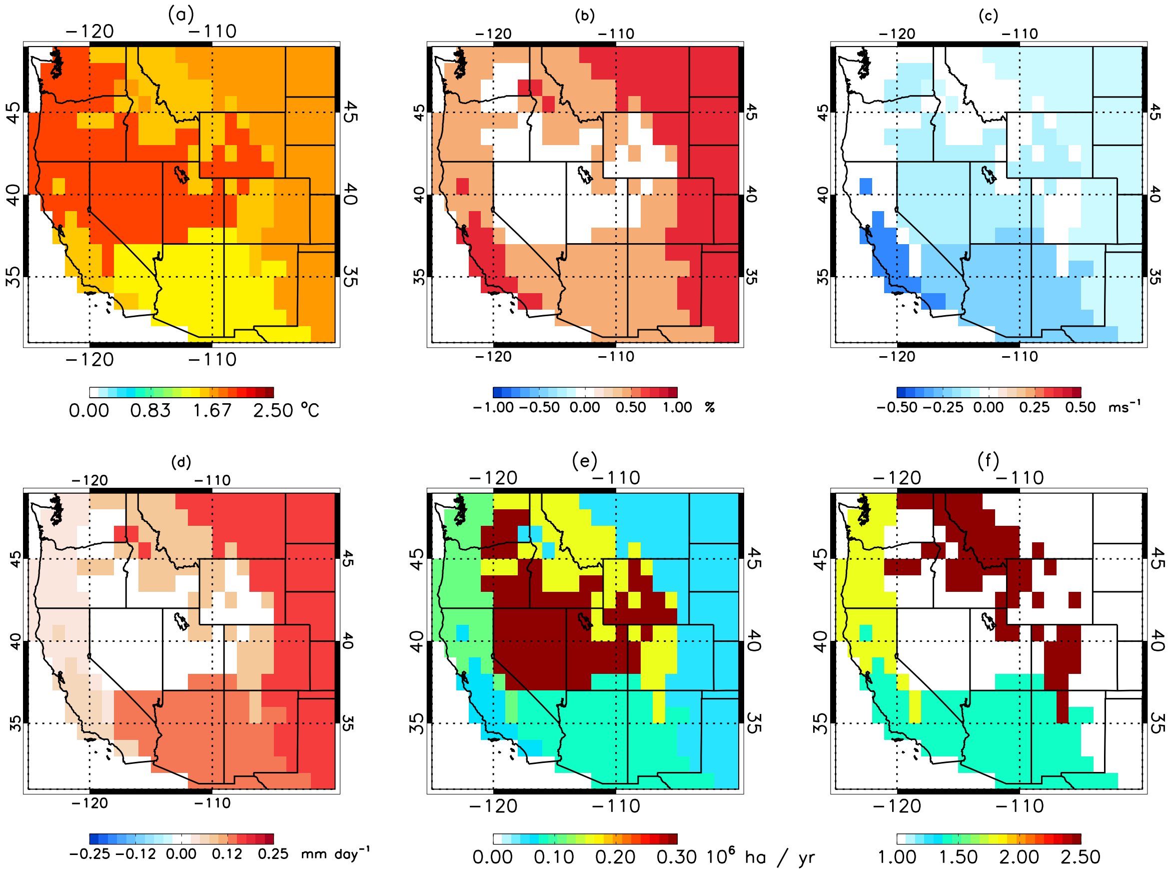


Figure 4. Simulated 1996-2055 change in May-October local noon meteorology using the GISS GCM and IPCC A1B emissions scenario. Values are the difference between 10-year means for 1996-2005 and 2046-2055. (a) surface temperature, (b) relative humidity, (c) wind speed, (d) 24-hr accumulated rainfall. Wildfire area burned predicted by our regression equations and GCM meteorology for (e) present day (1996-2005) and (f) ratio of predicted area burned 2046-2055:1996-2005.

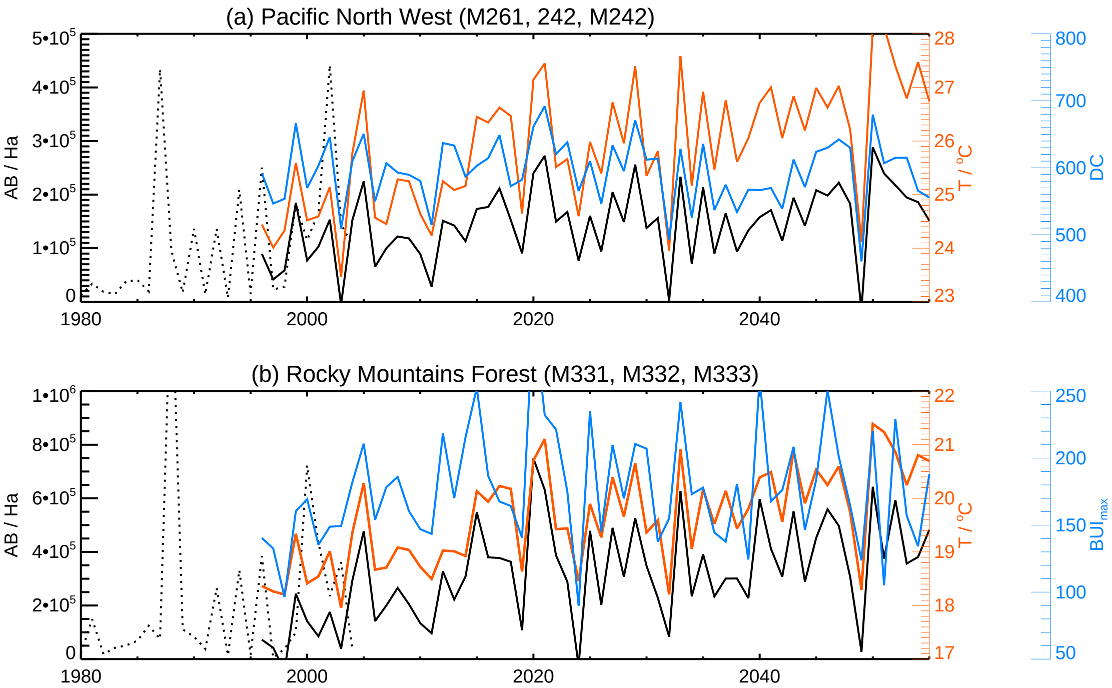


Figure 5. Annual area burned and May-October values of predictors used in regression equations for (a) Pacific Northwest and (b) Rocky Mountain Forest ecoregions between 1980 and 2055. Observed area burned (dotted black line) and predicted area burned (solid black line). Temperature (red) and drought codes (blue) are calculated using the GISS GCM and FWI model.

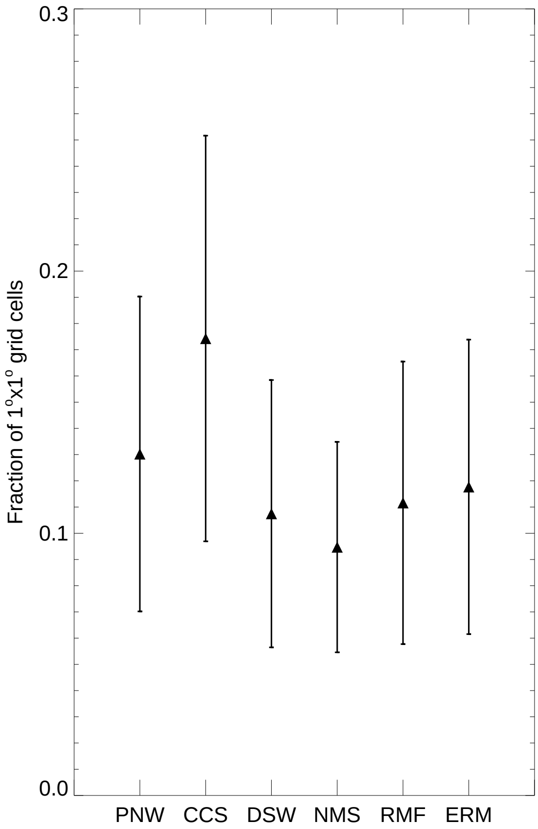


Figure 6. Fraction of 1°x1° grid squares (mean - solid symbols, error bars one standard deviation) within each ecoregion that contain 70% of area burned in any year calculated for the period 1980-2004. Ecoregions are as follows PNW, Pacific Northwest; CCS, Californian Coastal Shrub; DSW, Desert Southwest; NMS, Nevada Mountains/Semi-desert; RMF, Rocky Mountains Forest and ERM, Eastern Rocky Mountains/Great Plains.

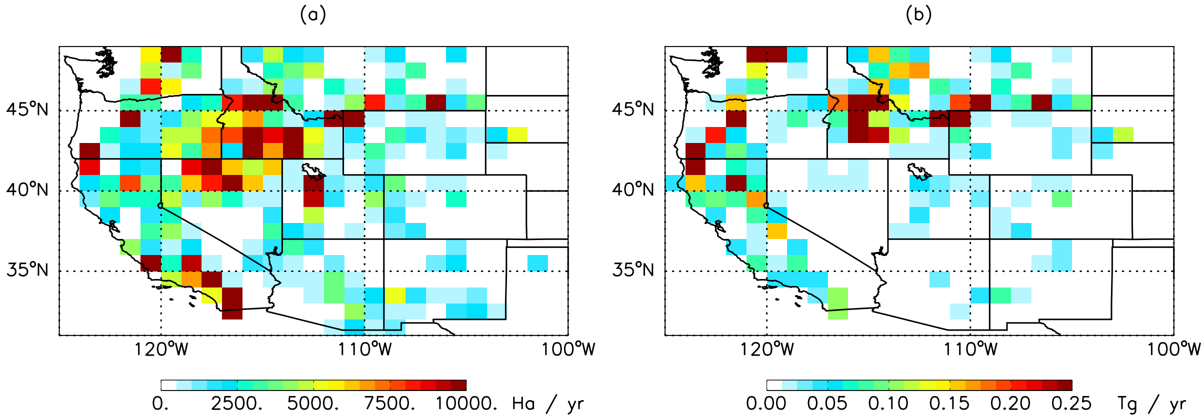


Figure 7. Annual mean (a) observed area burned and (b) dry biomass consumption for the period 1980-2004.

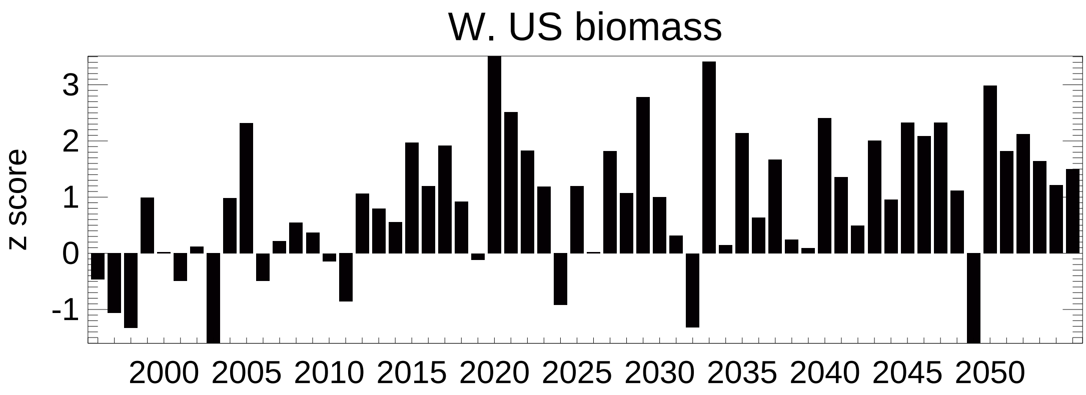


Figure 8. Predicted dry biomass consumption by wildfires in the western United States between 1996 and 2055 shown as a z-score, or standardized departure (the number of standard deviations away from the 1996-2005 mean).

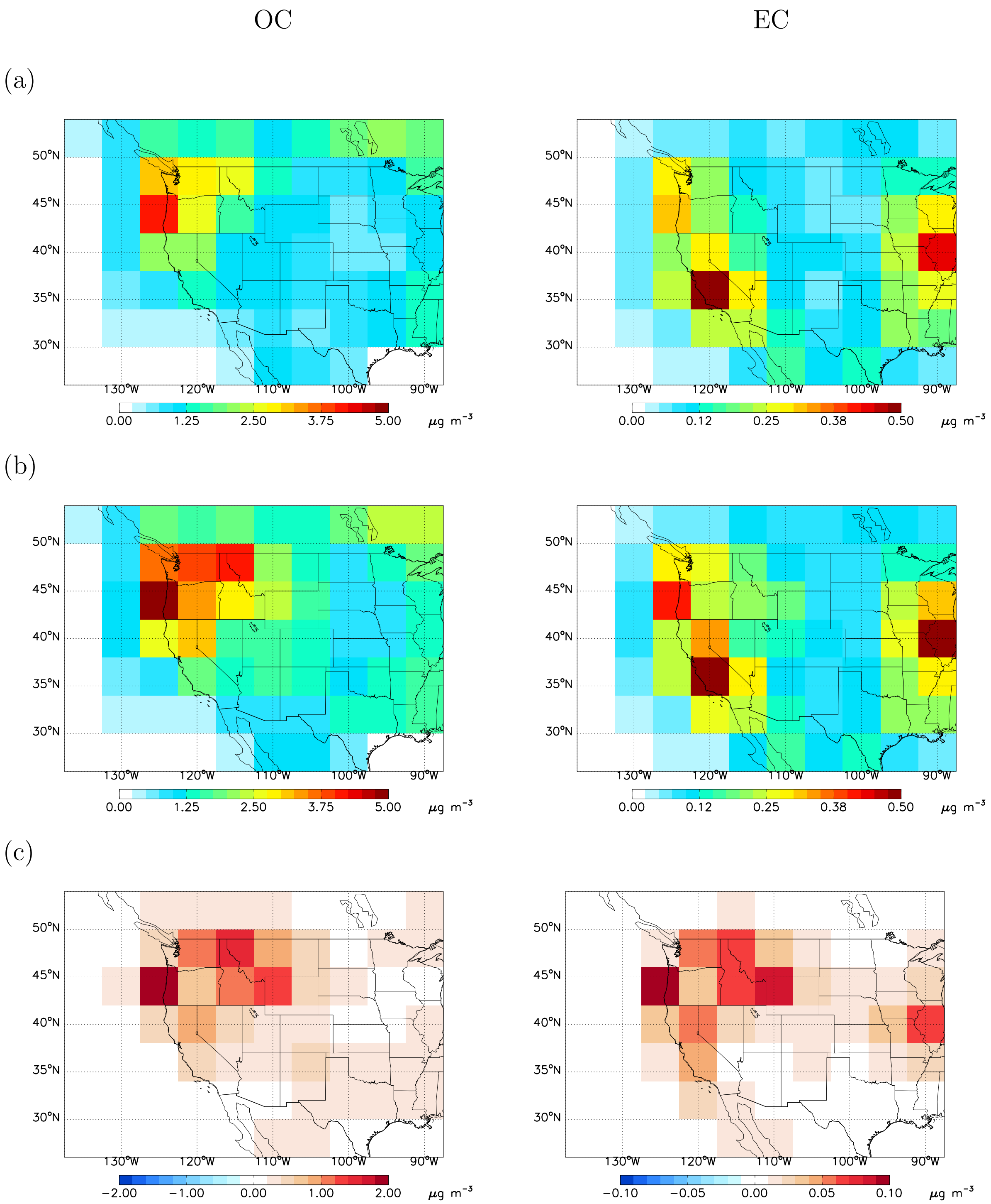
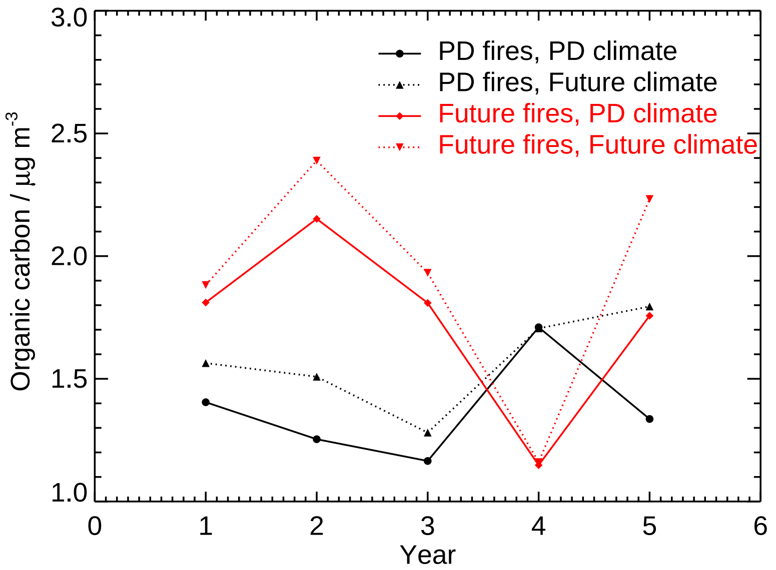


Figure 9. Simulated summertime (June-August) mean surface OC (left hand panels) and EC (right hand panels) concentrations over the western United States during (a) 1996-2000 and (b) 2046-2050. (c) The difference between simulated concentrations in 2046-2055 and 1996-2005. Units are μg m^{-3}.

(a)



(b)

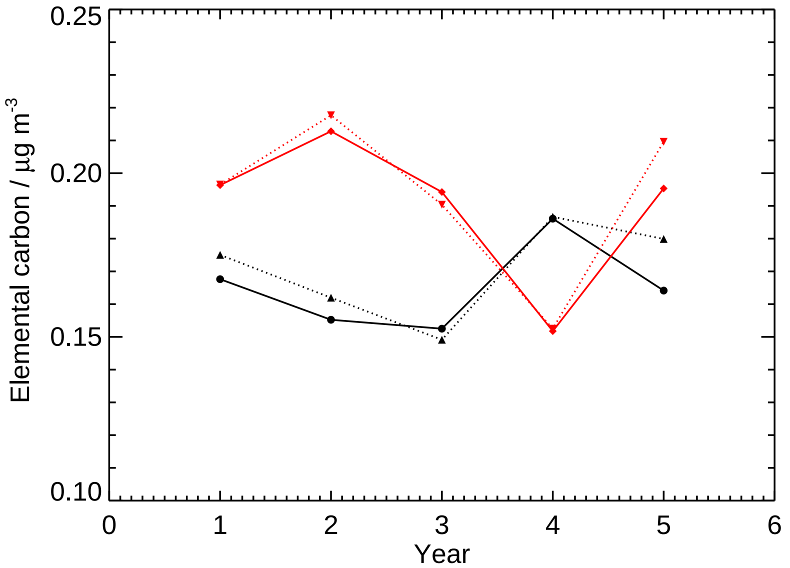


Figure 10. Simulated summertime average (June-August) surface concentrations of (a) OC and (b) EC in the western United States (31°-49°N, 125°-100°W) for (1) Present day (PD) wildfires (1996-2000) and present day climate (black circles), (2) Present day wildfires and future (2046-2050) climate (upwards triangles), (3) Future wildfires and present day climate (red circles), (4) Future wildfires and future climate (downwards triangles).

Table 1. Area burned regressions for aggregated ecoregions (from *Bailey et al.* [1994] ecosystem classes) in the western United States.

Ecoregion	Bailey Ecosystem Classes [a]	Mean elevation (m)	No. of met stations	R^2	Area burned / ha [b]
Pacific North West	M261,242, M242	1040	94	52%	$= -3.1\times10^6 + 9.4\times10^4$ T $+ 1.7\times10^3$ DC
Californian Coastal Shrub	262,M262 261	635	32	24%	$= -3.6\times10^6 + 3.4\times10^4\ T_{max} + 2.6\times10^4$ FFMC
Desert South West	322,321, M313,313	1600	61	49%	$= -1.64\times10^6 + 6.3\times10^4$ T + 296 DC_{max}
Nevada-Mtns/ Semi-desert	341,M341, 342	1740	22	37%	$= 3.9\times10^5 + 1.2\times10^4\ FWI_{max} - 1.4\times10^6$ Rain
Rocky Mtns. Forest	M331,M332, M333	1760	60	48%	$= -6.55\times10^6 + 3.2\times10^5$ T $+ 5.3\times10^3\ BUI_{max}$
E. Rocky Mtns./ Great Plains	331,315	1300	8	57%	$= -3.6\times10^5 + 3.4\times10^4$ DSR

[a] Description of Bailey ecosystems appear in Fig. 1. For each ecoregion the number of meteorological stations and the mean elevation of the stations is shown.

[b] Predictors are chosen from maximum and mean daily May through October values of meteorological variables and components of the Canadian Fire Weather Index System: Temperature (T), Drought Code (DC), Fine Fuel Mositure Code (FFMC), Fire Weather Index (FWI), accumulated 24-hour rainfall (Rain), Build-up Index (BUI), Drought Severity Rating (DSR).

Table 2. Annual mean observed (1980-2004) and simulated (present day, PD and future, F) area burned$\pm$ 1σ by ecoregion in the western United States

Ecoregion	Area burned / 10^5 ha Observed 1980-2004	Predicted 1996-2005- (PD)	Predicted 2046-2055 (F)	Ratio (F)/(PD)	Stand. Depart.[a]	Slope[b] $\pm1\sigma$ (ha yr^{-1})	P-value for slope
Pacific North West	1.08±0.39	1.08±0.70	1.92±0.79	1.78	1.23	1440±470	<0.01
California Coastal Shrub	0.59±0.17	0.60±0.43	0.84±0.31	1.38	0.61	320±310	0.15
Desert South West	0.74±0.14	0.81±0.22	1.16±0.18	1.43	1.42	690±160	<0.01
Nevada Mtns/Semi-desert	2.84±0.71	3.04±1.03	3.14±0.67	1.03	0.13	-140±590	0.41
Rocky Mountain Forest	2.07±0.71	1.53±1.52	4.19±1.76	2.75	1.44	5010±1220	<0.01
E. Rocky Mnts/Great Plains	0.78±0.26	0.55±0.85	0.50±0.67	0.91	-0.07	-400±540	0.23

[a] The standardised departure is the absolute change [F-PD] divided by the standard deviation [$\sigma_{(1996-2055)}$] in predicted area burned.

[b] The trend in predicted area burned (1996-2055) is fitted using linear regression and the slope of the best-fit line is reported.

Table 3. Present day (1996-2005) and future (2046-2055) May-October values of predictors [a] simulated using the GISS GCM and FWI system and used to calculate area burned.

Ecoregion	Simulated mean 1996-2005	Simulated mean 2046-2055	Standardised departure[b]	p-value[c]	% contribution[d]
Pacific North West					
DC	595	605	0.2	0.7	10
T / ^{o}C	24.9	26.9	1.7	<0.01	90
California Shrub					
T_{max} / ^{o}C	37.7	39.2	1.1	<0.01	95
FFMC	90.4	90.5	0.1	0.90	5
Desert South West					
T / ^{o}C	26.5	27.9	1.7	< 0.01	108
DC	590	566	-0.5	0.24	-8
Semi-desert					
FWI_{max}	92.1	95.0	0.3	0.38	180
Rain /mm day^{-1}	0.54	0.56	0.1	0.85	-80
Rocky Mountain Forest					
T /^{o}C	18.8	20.4	1.8	< 0.01	80
BUI_{max}	153	176	0.6	0.23	20
Great Plains					
DSR	5.9	5.7	-0.1	0.38	100

[a] See Table 1. Definition of predictors is in footnote of Table 1.

[b] Standardised departure is the future minus present day divided by the standard deviation for each predictor.

[c] Student's t-test calculated from the difference between the present day and future simulated means.

[d] The percentage contribution to the change in area burned is calculated for each predictor using the regressions in Table 1 and the change in predictor reported here.

Table 4. Annual mean dry biomass consumption by wildfire in the western United States.

	Annual mean biomass consumption / Tg			p-value[a]
	Observed	Simulated		
Ecoregion	1980-2004	1996-2005	2046-2055	
Pacific North West	4.23	6.33	11.31	0.04
California Coastal Shrub	0.46	0.61	0.82	0.36
Desert South West	0.39	0.30	0.42	0.05
Nevada Mtns/Semi-desert	1.02	1.43	1.48	0.66
Rocky Mountain Forest	6.06	4.19	11.51	<0.01
E. Rocky Mnts/Great Plains	2.07	0.97	0.88	0.88
Western U.S. Total	14.2	13.8	26.4	0.01

[a] Student's t-test p-value calculated from the difference between the present day and future simulated means.