

1 **Impacts of climate change from 2000 to 2050 on**
2 **wildfire activity and carbonaceous aerosol**
3 **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

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

53 Records of wildfire show increasing area burned in Canada [*Stocks et al.*, 2003; *Gillett*
54 *et al.*, 2004; *Kasischke and Turetsky*, 2006], Alaska [*Kasischke and Turetsky*, 2006] and the
55 western United States [*Westerling et al.*, 2006] over the past few decades. In the western
56 United States annual average forest wildfire area burned during 1987 to 2003 was more
57 than six times that during 1970 to 1986 [*Westerling et al.*, 2006]. In addition to climate,
58 wildfire behavior is also modified by forest management and fire suppression [*Allen et al.*,
59 2002; *Noss et al.*, 2006], so understanding the reasons for this change is complicated by

60 simultaneous changes in climate, land use, fire suppression and fire reporting that have
61 occurred over this period. However, changes in climate were likely the main drivers for
62 increases in area burned both in the western United States [*Westerling et al.*, 2006] and
63 Canada [*Gillett et al.*, 2004; *Kasischke and Turetsky*, 2006; *Girardin*, 2007]. Increases
64 in forest wildfires in the western United States have been driven largely by earlier spring
65 snowmelt and increasing spring and summertime temperatures; mean March-August tem-
66 peratures for 1987-2003 were 0.87 K warmer than those in 1970-1986 [*Westerling et al.*,
67 2006].

68 Several studies have estimated the impacts of future climate change on wildfire. *Flan-*
69 *nigan and Van Wagner* [1991] used three different GCMs to predict on average a 46%
70 increase in seasonal severity rating (SSR, a measure of fire weather) across Canada under
71 a 2 x CO₂ scenario. Similar results were found by *Flannigan et al.* [2000] who used two
72 GCMs to predict a 10-50% increase in SSR across much of North America under the same
73 scenario. Longer future fire seasons in Canada were predicted by *Stocks et al.* [1998] and
74 *Wotton and Flannigan* [1993]. Increased future fire danger has also been predicted for
75 Russia [*Stocks et al.*, 1998], the western United States [*Brown et al.*, 2004; *Westerling and*
76 *Bryant*, 2008] and the European Mediterranean area [*Moriondo et al.*, 2006]. *Westerling*
77 *and Bryant* [2008] predict a 10-35% increase in large fire risk by mid-century in California
78 and Nevada, depending on the greenhouse gas emissions scenario and GCM used. Large
79 regional variation in future wildfires are predicted by Regional Climate Models (RCMs),
80 including decreased fire danger in parts of eastern Canada due to increased precipitation
81 [*Bergeron and Flannigan*, 1995; *Flannigan et al.*, 2001].

82 Many of the above studies predict changes in fire indices, but estimates of emissions from
83 fires require predictions of area burned. *Flannigan et al.* [2005] investigated relationships
84 between climate and the areas of fires in Canada. Stepwise linear regression was used to
85 derive the best predictors of area burned, chosen from meteorological variables (surface
86 temperature, rainfall, wind speed and relative humidity) and calculated values of forest
87 fuel moisture from the Canadian Fire Weather Index (FWI) System. Temperature and
88 fuel moisture explained between 36% and 64% of the variance in monthly area burned
89 depending on the ecosystem. The Canadian and Hadley Centre GCMs were used to
90 predict increases in area burned of 74-118% under a $3 \times \text{CO}_2$ scenario. RCMs have also
91 been used to study wildfire area burned in limited regions of Canada. For the boreal
92 forests of Alberta, *Tymstra et al.* [2007] used an RCM to predict a 13% increase in area
93 burned in a $2 \times \text{CO}_2$ scenario and a 30% increase in a $3 \times \text{CO}_2$ scenario. Most of these
94 studies did not account for any future changes in ignition sources. *Price and Rind* [1994]
95 used empirical lightning and fire models along with the Goddard Institute for Space Studies
96 (GISS) GCM to predict that more intense convection under a $2 \times \text{CO}_2$ scenario leads to
97 increased lightning and a 78% increase in area burned in the United States.

98 Despite these efforts to predict the effect of future climate on wildfires, there have not
99 been studies of the impact of these future wildfires on air quality. In this paper we predict
100 how wildfires in the western United States will respond to changes in climate between
101 the present day and 2050 and evaluate the impacts on aerosol air quality. We apply the
102 technique of *Flannigan et al.* [2005] to the western United States, building regressions
103 between observed wildfire area burned [*Westerling et al.*, 2003] and observed climate.
104 Projections of future climate, calculated by the GISS GCM, are used to predict changes

105 in wildfire area burned. We use the GEOS-chem chemical transport model (CTM) driven
106 by meteorology from the GISS model to quantify the impact of changing wildfire on
107 carbonaceous aerosol concentrations.

2. Predicting wildfire emissions for 2000-2050

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

2.1. Area Burned Predictions

111 We extend the approach of *Flannigan et al.* [2005] to the western United States, building
112 regressions of observed area burned with surface meteorological data and output from the
113 FWI model. Observed area burned was taken from the database of *Westerling et al.*
114 [2003]. They used reports from various agencies in the United States that provided the
115 area burned on federal land, and the start and end date of individual fires, from 1980 to
116 2000. This database has been extended to 2004. *Westerling et al.* [2003] assumed that
117 the fires burn entirely in the month during they started (end dates are often unreliable),
118 and the areas were aggregated on a grid of 1° x 1°. Because the gridded database used
119 only the start date of each fire, it may not accurately reflect the seasonal dependence of
120 each fire season. In addition, the wildfire timeseries is relatively short, and if there are
121 only a few extreme events, it is difficult to fit with the least squares approach used here.
122 For these reasons we chose to predict annual area burned.

123 Area burned was binned according to the ecological stratification of *Bailey et al.* [1994].
124 This system defines 18 ecosystem classes in the western United States. These ecosystems

125 were further aggregated to produce 6 ecoregions with similar vegetation and climate, as
126 shown in Fig. 1. We tested our regressions with the original 18 ecosystems, but found
127 we could better fit area burned for the larger ecoregions, as did *Flannigan et al.* [2005]
128 for Canada. This is probably caused by meteorological factors that influence area burned
129 operating at synoptic scales, and larger spatial units providing some statistical smoothing
130 of noisy data for area burned. We use these 6 ecoregions (Pacific North West, California
131 Coastal Shrub, Desert South West, Nevada Mountains/Semi-desert, Rocky Mountains
132 Forest and Eastern Rocky Mountains/ Great Plains) for the rest of this work.

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

145 The calculated daily values of the four meteorological variables were used as input to
146 the Canadian FWI System [*Van Wagner, 1987*]. The model calculates daily fuel moisture
147 codes and fire severity indices using these four variables to track changes in forest fuel

148 moisture. A schematic of this model is shown in Fig. 2. The fuel moisture codes de-
149 scribe the moisture content of three distinct fuel layers in the forest floor. The Fine Fuel
150 Moisture Code (FFMC) represents surface fuel litter and changes rapidly with short-term
151 changes in atmospheric moisture (time lag of 2/3 day). The Duff Moisture Code (DMC)
152 represents loosely compacted organic layers (time lag of 15 days) and the Drought Code
153 (DC) represents deep layers of compacted fuel and reacts to seasonal droughts (time lag
154 of 52 days). The fire severity ratings combine information from the fuel moisture codes
155 to give an indication of the fire danger or rate of fire spread. The Build-up Index (BUI)
156 combines DMC and DC and is an indication of the availability of fuel for consumption.
157 The potential rate of spread of a fire is calculated by combining wind speed and FFMC
158 to give the Initial Spread Index (ISI). The ISI and BUI are combined to give the Fire
159 Weather Index (FWI) which is a rating of fire intensity. The Drought Severity Rating
160 (DSR) is an exponential function of the FWI and gives an indication of the difficulty of
161 fire control.

162 Linear forward stepwise regression was used for each of the six ecoregions with annual
163 area burned as the predictand. For predictors we used the maximum and mean of the
164 daily May to October values of temperature, relative humidity and wind speed and the 7
165 output fields from the FWI model (described above). In addition we used May to October
166 mean daily rainfall and total May to October rainfall. This gives 22 potential predictors.
167 We used the same test for significance as *Flannigan et al.* [2005]; terms were accepted only
168 if they met a significance level (p value) of 0.15. The predictor with the highest correlation
169 coefficient was added to the regression first. Predictors were then added in the order that
170 maximised the correlation coefficient, until the correlation coefficient did not increase by

171 a preselected amount (typically 2%), or until a predictor was selected that resulted in a
172 non-physical relationship between area burned and fuel moisture. In general, 2 predictors
173 were selected for each ecoregion. We tested our method using both area burned and
174 natural logarithm of area burned. We found similar correlation coefficients with the two
175 predictands. For the rest of this work prediction of linear area burned was used as this
176 results in total predicted area burned being equal to observed area burned. This is not
177 the case when logarithm of area burned is predicted.

178 Figure 3 shows a comparison of observed and predicted annual area burned in the
179 Pacific Northwest and Rocky Mountain Forest ecoregions. The observations show large
180 interannual variability in area burned, with a range of 7500 ha/year to 440,000 ha/year in
181 the Pacific Northwest and 4800 ha/year to 1.45 million ha/year in the Rocky Mountain
182 Forest. In the Pacific Northwest the regression explains 52% of this interannual variability.
183 The chosen predictors for this region are mean drought code and mean temperature, for
184 which the individual correlation coefficients (R^2) are 46% and 43% respectively. The
185 greatest observed area burned occurred in 1987 and 2002 coincident with high DC and T.
186 Predicted area burned is also maximum during these two years but is underestimated by
187 about 40%. In the Rocky Mountain Forest the regression explains 47% of the variability
188 in annual area burned. The best predictors for this region are mean temperature and
189 maximum build-up index for which the individual correlation coefficients (R^2) are 42%
190 and 40% respectively. The regression underpredicts the largest fire year in 1988 by about
191 60%, but other large fires years (e.g., 2000 and 2001) are well predicted.

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

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

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

2.2. Simulation of future area burned

206 To calculate future area burned, we archived daily mean temperature, relative humidity
207 and local noon windspeed as well as 24-hour accumulated rainfall from the GISS simulation
208 for 2000-2050. We used the 'q-flux' version of the GISS GCM 3 [*Rind et al.*, 2007], which
209 has a horizontal resolution of 4° x 5° and 23 vertical sigma levels between the surface and
210 0.002 hPa. In the q-flux version, ocean heat transport fluxes are kept fixed while ocean
211 temperatures and ocean ice respond to changes in climate. Observed concentrations of
212 well-mixed greenhouse gases, ozone, and aerosols were used for the model spinup between
213 1950 and 2000, starting from a climate equilibrium [*Hansen*, 2002]. For 2001 to 2055 we
214 used concentrations of well-mixed greenhouse gases from the IPCC SRES A1B scenario,
215 with CO₂ calculated using the Bern-CC model [*Houghton*, 2001]. Under this scenario CO₂

216 mixing ratios reach 522 ppm by 2050. We assumed no changes in ozone or aerosols from
217 2001 to 2055 for the purpose of calculating climate change. This model predicts global
218 mean July temperatures to increase by 1.8°C from 2000 to 2050.

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

226 Fig. 4 shows the simulated changes between 2000 and 2050 in mean May through
227 October noon values of the four meteorological variables over the western United States;
228 we compare the means for 1996-2005 and for 2046-2055. Temperatures increase across the
229 western United States by 1-3°C, with the largest increases in the Pacific Northwest and
230 Nevada Mountains/Semi-desert ecoregions. The projected change in temperature is large,
231 1.5-1.8 times the standard deviation in May-October mean temperature, even though
232 2049 is a relatively cold year for the western United States. Precipitation and relative
233 humidity increase by 7% and less than 2% respectively across the western United States
234 with the greatest increases in the Eastern Rocky Mountains/Great Plains and Desert
235 Southwest ecoregions. Mean windspeeds are projected to decrease slightly throughout
236 the western United States. These climate projections lie within the ensemble of climate
237 model predictions [*Seager et al.*, 2007; *Christensen*, 2007], giving us confidence that our
238 results are robust.

239 We applied the adjusted GCM meteorology to our area burned regression model to
240 predict annual ecoregion area burned from 1996 to 2055. Table 2 shows the average
241 observed area burned for 1980 to 2004 and average calculated area burned for a 10-year
242 period in the present day (1996 to 2005) and in the future (2046 to 2055) for each of the 6
243 ecoregions. Average area burned in the present day is calculated with a normalised mean
244 bias of +10% to -25% depending on the region. Fig. 4e shows simulated annual area
245 burned for 1996-2005 and Fig. 4f shows the ratio of area burned in 2046-2055 to that in
246 1996-2005.

247 Total area burned across the western United States is projected to increase by 54%
248 for 2046-2055 relative to 1996-2005. This projected increase is significant (Student's t
249 test $p=0.03$). Area burned is predicted to increase in all regions except the Eastern
250 Rocky Mountains/Great Plains where the change is not significant. Statistically signif-
251 icant ($p<0.05$) increases in area burned are projected for the Rocky Mountain Forest
252 (78%), Pacific Northwest Forest (175%) and Desert Southwest (43%) ecoregions (see Ta-
253 ble 2). In these ecoregions area burned by mid-century is predicted to increase by more
254 than one standard deviation. We used our regression equations (Table 1) along with the
255 predicted changes in meteorological and FWI parameters to quantify the contributions of
256 the different predictors to the change in predicted area burned (see Table 3). Simulated
257 increases in temperature (Fig. 4) are responsible for more than 80% of the predicted
258 increase in area burned in these ecoregions.

259 For most of the West, temperature plays the main role in driving future changes in
260 area burned. However, the small (but insignificant) reduction in area burned in the
261 Great Plains/Eastern Rocky Mountains is due to increased precipitation simulated by

262 the GCM. In the Nevada Mountains/Semi-desert and to a lesser extent in the Desert
263 Southwest ecoregions the impact of increasing temperature is partly offset by increasing
264 precipitation; there is no significant change in area burned in the former region and a 43%
265 increase in the Desert Southwest ecoregion.

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

2.3. Production of wildfire emissions

272 To calculate emissions from wildfires, we took the following steps. We first converted
273 annual area burned to monthly area burned by using the average observed seasonal vari-
274 ability of wildfire in each ecoregion in 1980-2004. We assumed that the seasonality of
275 wildfire remains the same in the future. Calculated ecoregion area burned was mapped
276 onto a $1^\circ \times 1^\circ$ grid using the observed area burned data to constrain the typical spatial
277 extent of fires within each ecoregion. Figure 6 shows the fraction of $1^\circ \times 1^\circ$ grid squares
278 that contain 70% of observed annual area burned in any one year in each of the six ecore-
279 gions. For all ecoregions, 70% of area burned in a particular year occurs in 5-25% of
280 the ecoregion. To match this observed behavior, we place 70% of projected area burned
281 in 10% of $1^\circ \times 1^\circ$ grid squares in each ecoregion. We locate these grid squares randomly
282 within each ecoregion. The remaining 30% of area burned was averaged across the re-
283 maining 90% of grid squares within the ecoregion. To check for bias introduced by the

284 random placement of wildfires within each ecoregion, we created a 100-member ensemble
285 of simulations of yearly biomass consumption, each with a different randomly chosen set
286 of wildfire locations. Our results showed only a 1% one-sigma variation in total biomass
287 consumption over the simulation period.

288 Emissions of carbonaceous aerosol from wildfires were calculated using the predicted
289 $1^\circ \times 1^\circ$ wildfire area burned maps, ecosystem specific fuel loadings from the USDA Forest
290 Service [McKenzie *et al.*, 2007] and emission factors from Andreae and Merlet [2001]. The
291 fuel loadings are available on a grid of $0.025^\circ \times 0.025^\circ$, and we formed an area weighted
292 mean for each $1^\circ \times 1^\circ$ grid-box. We assume wildfires occur with 25% high, 25% medium and
293 25% low severity and that 25% of predicted area burned remains unburned, based on an
294 analysis of the largest wildfires in 2002 in the continental United States [Randall, 2004].
295 We assume that fuel loadings and fire severity do not change between present day and
296 2050, so that the emissions of carbonaceous aerosol per unit area burned do not change
297 over the simulation period.

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

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

309 The calculated annual mean dry biomass consumption based on observed area burned
310 is 14.2 Tg for 1980-2004. Predicted mean dry biomass consumption in the western United
311 States, averaged over the 100-member ensemble of simulations, increases from ~ 13.8
312 Tg/year for 1996-2005 to ~ 26.4 Tg/year for 2046-2055, an increase of $\sim 90\%$ (see Table 4).
313 This increase is statistically significant ($p < 0.01$). The linear trend in biomass consumption
314 is 0.23 ± 0.07 Tg year $^{-1}$. Figure 8 shows the trend in predicted dry biomass consumption by
315 wildfire in the western United States for 1996-2055 plotted as the standardized departure
316 from the mean for 1996-2005 (Standardized departure $_i = [P_i - \bar{P}_{(1996-2005)}]/\text{standard}$
317 deviation($P_{1996-2005}$), where P_i is the biomass consumption in year i). A low fire year in
318 2046-2055 (except for 2049) is about 1 standard deviation above the 1996-2005 mean and
319 is equivalent to a high fire year during 1996-2005.

3. Simulations of atmospheric EC and OC

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

3.1. Model Description

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

326 species by *Wu et al.* [2007a] and for aerosols by *Liao et al.* [2007]. We described the GISS
327 model version used in this work in section 2.2.

328 Meteorological output from the GISS GCM was archived with 6-hour resolution (3
329 hours for surface quantities and mixing depths) and used as input to the CTM. We used
330 GEOS-Chem model version v7.04 (see <http://www-as.harvard.edu/chemistry/trop/geos>)
331 with the same spatial resolution as the GCM, $4^{\circ}\times 5^{\circ}$.

332 The model treats EC and OC with a hydrophobic and hydrophilic fraction for each
333 (giving 4 advected tracers). Combustion sources emit hydrophobic aerosol which become
334 hydrophilic with an e-folding time of 1.2 days [*Cooke et al.*, 1999; *Chin et al.*, 2002]. We
335 assumed that 80% of EC and 50% of OC emitted from primary sources are hydrophobic
336 [*Cooke et al.*, 1999; *Chin et al.*, 2002; *Chung and Seinfeld*, 2002]. Anthropogenic emissions
337 of OC over the United States are from *Cooke et al.* [1999] with the correction factor from
338 *Park et al.* [2003]. Biofuel OC emissions are from *Yevich and Logan* [2003] and from *Park*
339 *et al.* [2003] for the United States. In the western United States, we used fire emissions
340 calculated as described in section 2.3, using one member of the ensemble of simulations
341 with random placement of fires within each ecoregion. Outside of the western United
342 States we used climatological biomass burning emissions derived from *Lobert et al.* [1999]
343 with seasonality from *Duncan et al.* [2003]. Biomass burning emissions were emitted into
344 the boundary layer. Emissions of monoterpenes were calculated using *Guenther et al.*
345 [1995] and vary according to temperature and solar radiation. We did not account for
346 the effects of changing CO₂ concentrations [e.g., *Constable et al.*, 1999] or changing land
347 cover [*Sanderson et al.*, 2003] on monoterpene emissions from vegetation. We assumed a
348 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 $1.4 \mu\text{g m}^{-3}$ to $2.1 \mu\text{g m}^{-3}$ over 50 years (an increase of 40%) whereas EC increases from $0.18 \mu\text{g m}^{-3}$ to $0.21 \mu\text{g m}^{-3}$ (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

371 increase in carbonaceous aerosol concentrations occurs over the north-west United States
372 (Oregon, Washington, Idaho, western Montana and northern California) where absolute
373 OC increases $1\text{-}4\ \mu\text{g m}^{-3}$ (15-70%) and EC aerosol increases $0.05\text{-}0.2\ \mu\text{g m}^{-3}$ (10-70%).
374 These large increases in carbonaceous aerosol are caused by the large increase in area
375 burned simulated for the Pacific Northwest and Rocky Mountain Forest ecoregions (Table
376 2). The smaller increases in carbonaceous aerosol in the southwest (southern California,
377 Arizona, New Mexico) reflect the smaller predicted increases in wildfires in these areas.

378 To separate the impact of direct changes in wildfire emissions from the impact of chang-
379 ing climate on emissions of monoterpenes and on aerosol removal and transport, we per-
380 formed two sensitivity studies: one with present-day climate and future wildfire activity
381 and one with future climate and present-day wildfire activity. Figure 10 summarizes the
382 results for the western United States ($31^{\circ}\text{-}49^{\circ}\text{N}$, $125^{\circ}\text{-}100^{\circ}\text{W}$) for these scenarios and for
383 the standard present-day and future simulations described above. The effect of a cold
384 future summer (year 4) shows up clearly as a year with low regionally averaged concen-
385 trations of both OC and EC aerosol. Future wildfire emissions and future climate drive
386 an 18% increase in EC concentrations and a 40% increase in OC concentrations relative
387 to present day across the western United States (see above). Future wildfire emissions,
388 but present-day climate, result in EC concentration increasing by 17% and OC concen-
389 trations by 30%. Increased wildfire emissions in the future are therefore responsible for
390 the majority of the increase in carbonaceous aerosols, 75% for OC and 95% for EC.

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

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

4. Discussion and conclusions

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

411 Following the IPCC A1B greenhouse gas scenario, the GISS GCM predicts a 2 K in-
412 crease in summertime temperature and a $\sim 7\%$ increase in summertime precipitation by
413 mid-century in the western United States. These predicted changes in climate increase
414 projected area burned in the western United States in 2046-2055 by 54% relative to 1996-
415 2005. Predicted changes to area burned vary regionally, from no change to an increase of

416 175%, because of regional changes in simulated climate combined with varying ecosystem
417 response to a changing climate. The largest increases in area burned are projected for the
418 Pacific Northwest (78%) and Rocky Mountain Forest (175%) ecoregions where wildfire
419 appears to depend most strongly on temperature. This is consistent with the change in
420 wildfire activity observed in the western United States over the past few decades; sixty
421 percent of the six-fold increase in forest fire area burned that occurred between 1970-1986
422 and 1987-2003 was located in in the Northern Rockies, and 18% in the Sierra Nevada,
423 Cascades and coast ranges of Oregon and California [*Westerling et al.*, 2006]. Our method
424 projects little change in area burned by 2050 for the Nevada Mountains/Semi-desert and
425 Eastern Rocky Mountains/Great Plains ecoregions because simulated increases in precip-
426 itation compensate for increases in temperature in these regions.

427 We use the GEOS-chem CTM, driven by meteorology from the GISS GCM, to predict
428 changes in carbonaceous aerosol concentrations over the western United States. We pre-
429 dict that mean summertime OC concentrations in 2046-2050 increase by 40% (from 1.5 to
430 $2.1 \mu\text{g m}^{-3}$) and EC concentrations by 18% (from 0.18 to $0.22 \mu\text{g m}^{-3}$) relative to 1996-
431 2000. The largest projected increases are in the north-west United States, co-located with
432 the greatest increases in wildfire. Most of the increase in carbonaceous aerosol concentra-
433 tions (95% for EC and 75% for OC) is caused by increases in wildfire emissions, which are
434 predicted to increase by 90%. Changes in meteorology that occur between present day
435 and mid-century contribute about 5-10% of the predicted change in carbonaceous aerosol
436 concentrations. For OC, the remainder of the change (20%) is caused by the predicted
437 increase in monoterpene emissions, due to rising temperature, and the resulting increase

438 in secondary organic aerosol formation which has been previously predicted [*Heald et al.*,
439 2008].

440 In common with previous studies of future wildfires there are limitations in this study.
441 We did not account for changes to vegetation, ignition, the length of fire season or human
442 activity. Future wildfires may be modified by changes in the distribution of vegetation
443 caused either by direct anthropogenic land-use change or by climate change. In this paper,
444 we considered a 50-year timescale over which vegetation will not change substantially,
445 unless it is driven by wildfire [*McKenzie et al.*, 2004] or pest outbreaks [*Logan et al.*,
446 2003; *Hicke et al.*, 2006]. Our assumption of unchanging vegetation implies that future
447 increases in wildfire are not limited by the availability of vegetation. Even in large fire
448 years, less than 2% of an ecoregion typically burns, so this assumption is likely to be valid
449 over the timescales considered here. Over longer timescales, changes to fire activity will
450 change fire-return intervals, with potential impacts on vegetation and fuel loads [*Fellows*
451 *and Goulden*, 2008]. Over these longer timescales the future distribution of vegetation
452 may have an important impact on future wildfire emissions and air quality.

453 Wildfire severity may change in a changing climate, altering the burn severity and
454 emissions of carbonaceous aerosol per unit burned area. Here we have assumed that wild-
455 fire intensity remains unchanged over the simulation period. Changes to wildfire due to
456 changes in lightning frequency [*Price and Rind*, 1994] and change to anthropogenic igni-
457 tion [*Wotton et al.*, 2003] are also not considered here. A longer wildfire season is possible
458 in a future climate, and an earlier start to the wildfire season has been already been
459 observed in the western United States [*Westerling et al.*, 2006]. We predict annual area
460 burned and do not explore possible changes in the length of the fire season. Consequently,

461 we focused on the air quality impact of wildfires in summer (June - August). This is the
462 period of greatest wildfire activity and also the period when air quality degradation from
463 wildfires is at its worst. However, longer wildfire seasons in the future may extend the
464 negative impacts on air quality further into the spring and autumn.

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

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

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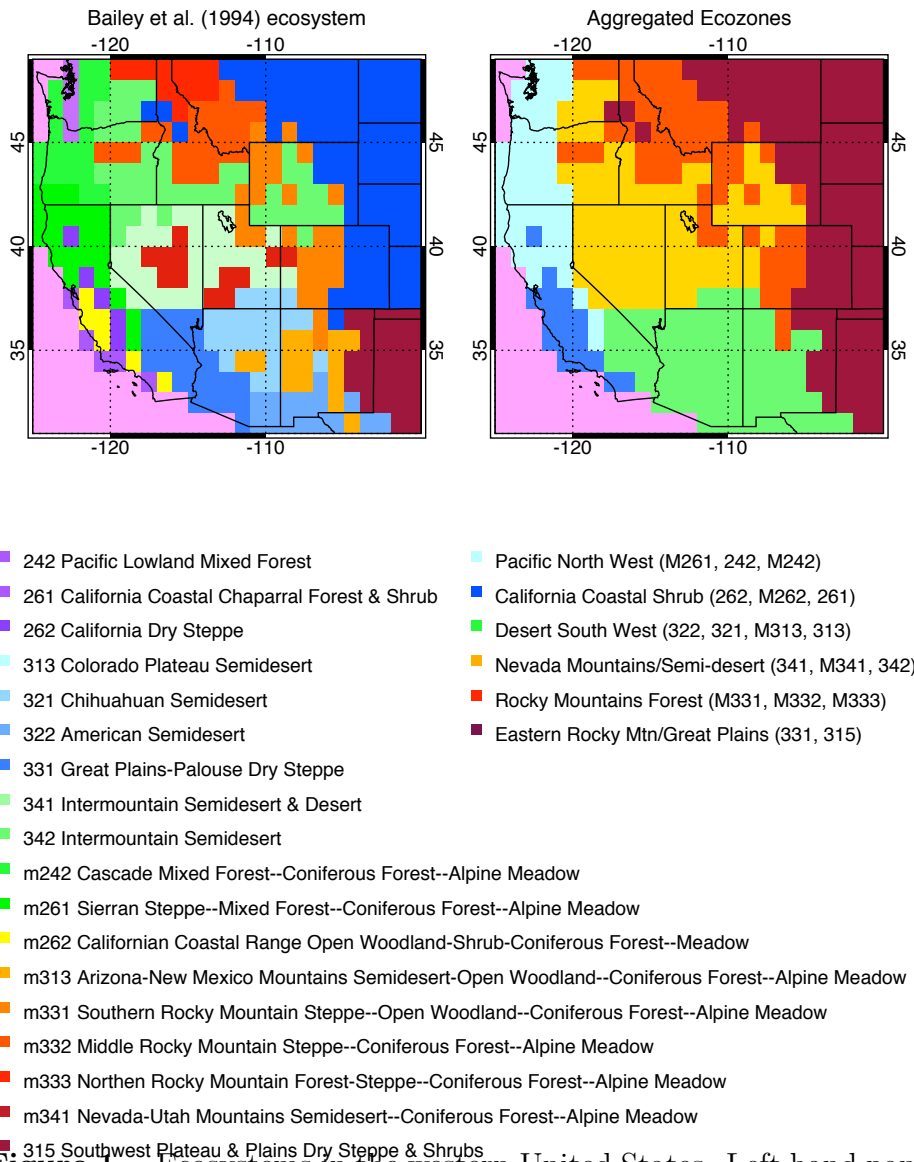


Figure 1. Ecosystems in the western United States. Left hand panel shows Bailey et al. [1994] ecosystem classes projected onto a 1° by 1° grid. Right hand panel shows aggregated ecosystems that are used in this analysis: Pacific Northwest, Californian Coastal Shrub, Desert Southwest, Nevada Mountains/Semi-desert,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

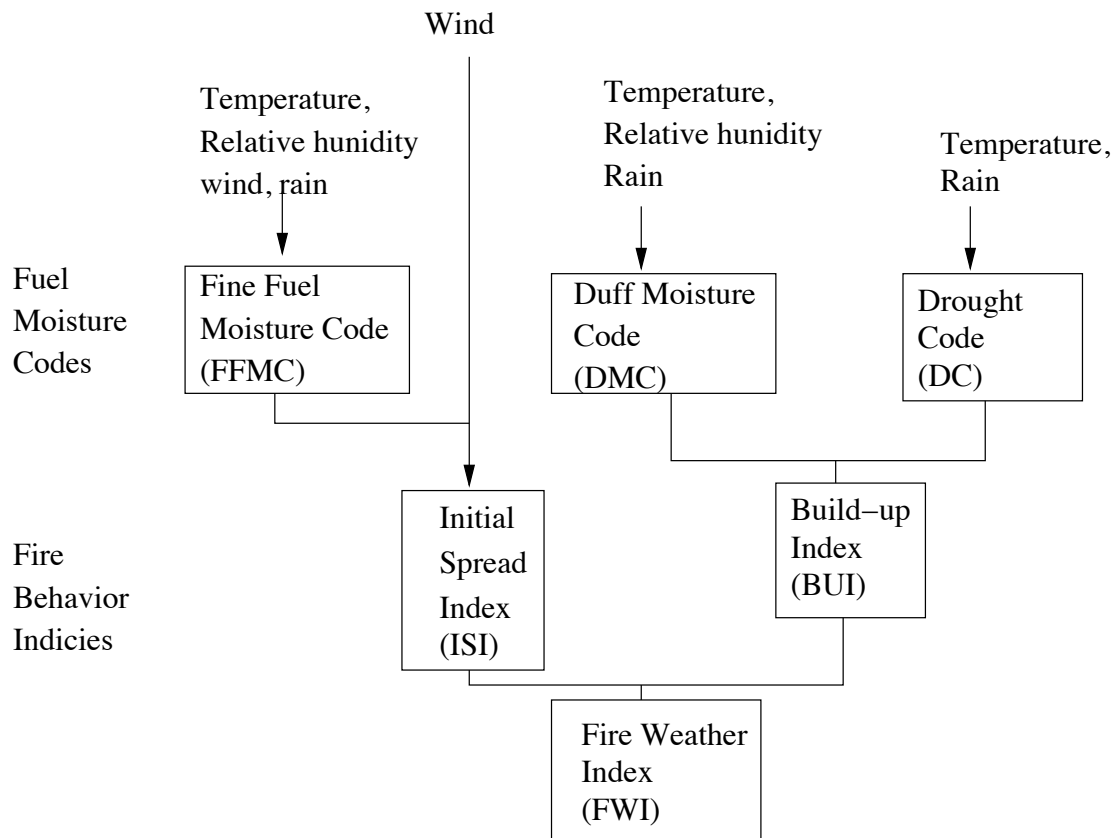


Figure 2. Schematic of the Canadian Fire Weather Index (FWI) System.

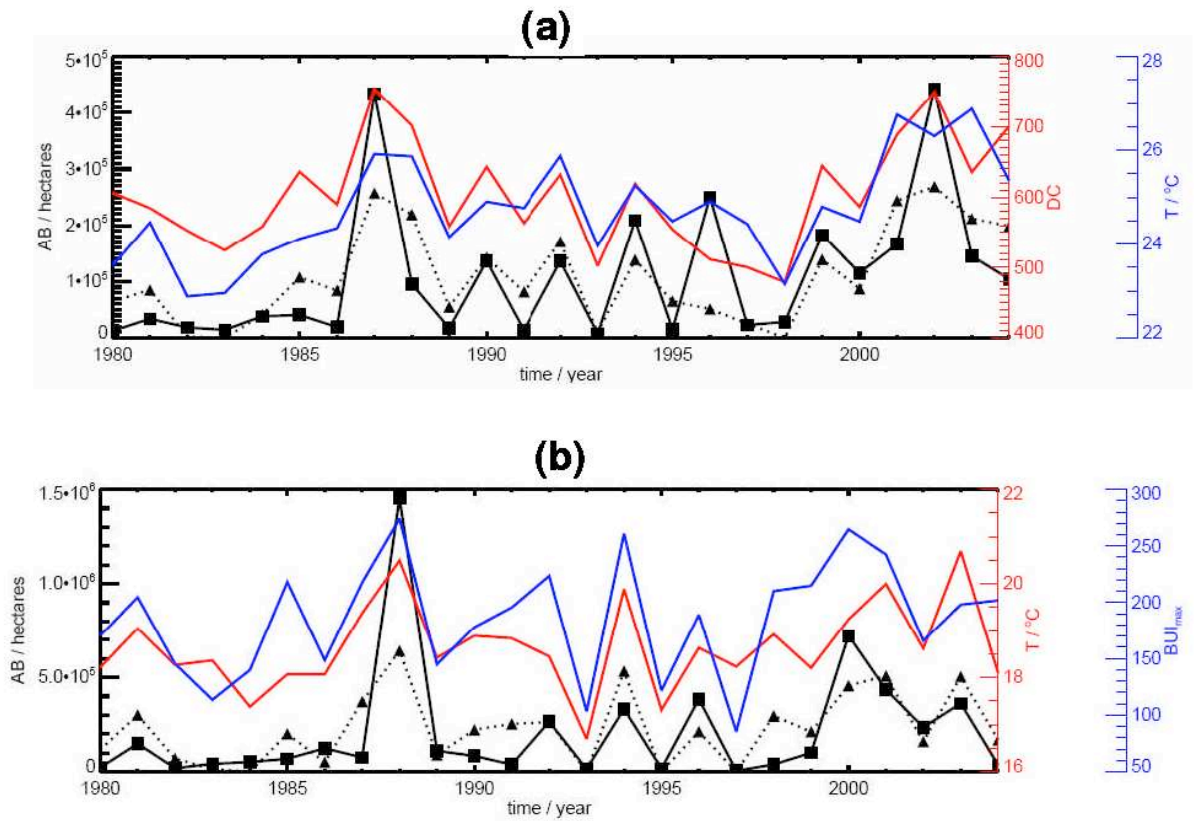


Figure 3. Annual area burned between 1980 and 2004 in (a) Pacific Northwest and (b) Rocky Mountain Forest ecoregions; Observed [*Westerling et al., 2003*] (filled squares) and predicted using stepwise linear regression (filled triangles). Also shown are the predictors chosen by the regression (mean or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

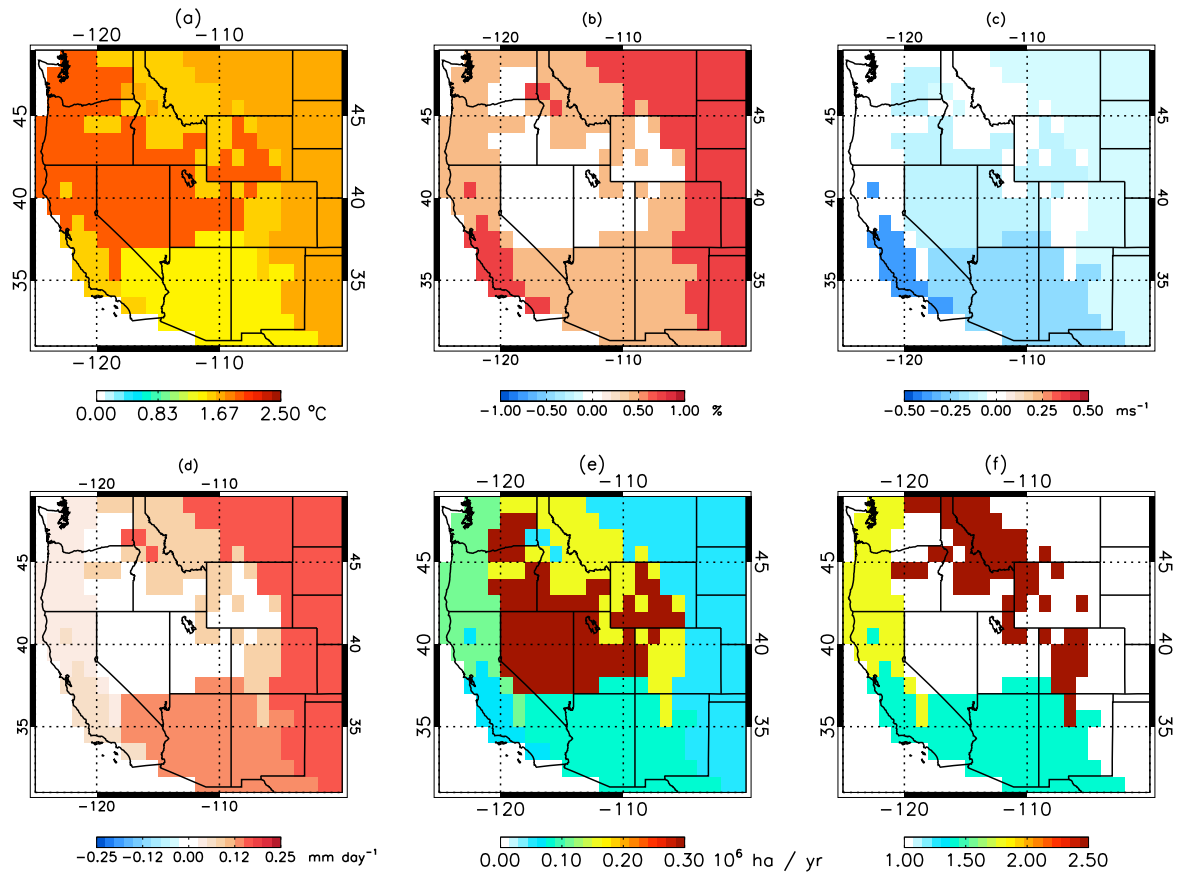


Figure 4. Simulated 1996-2055 change in May-October local noon meteorology using the GISS GCM and IPCC A1B emissions scenario. Values are the difference between 10-year means for 1996-2005 and 2046-2055. (a) surface temperature, (b) relative humidity, (c) wind speed, (d) 24-hr accumulated rainfall. Wildfire 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.

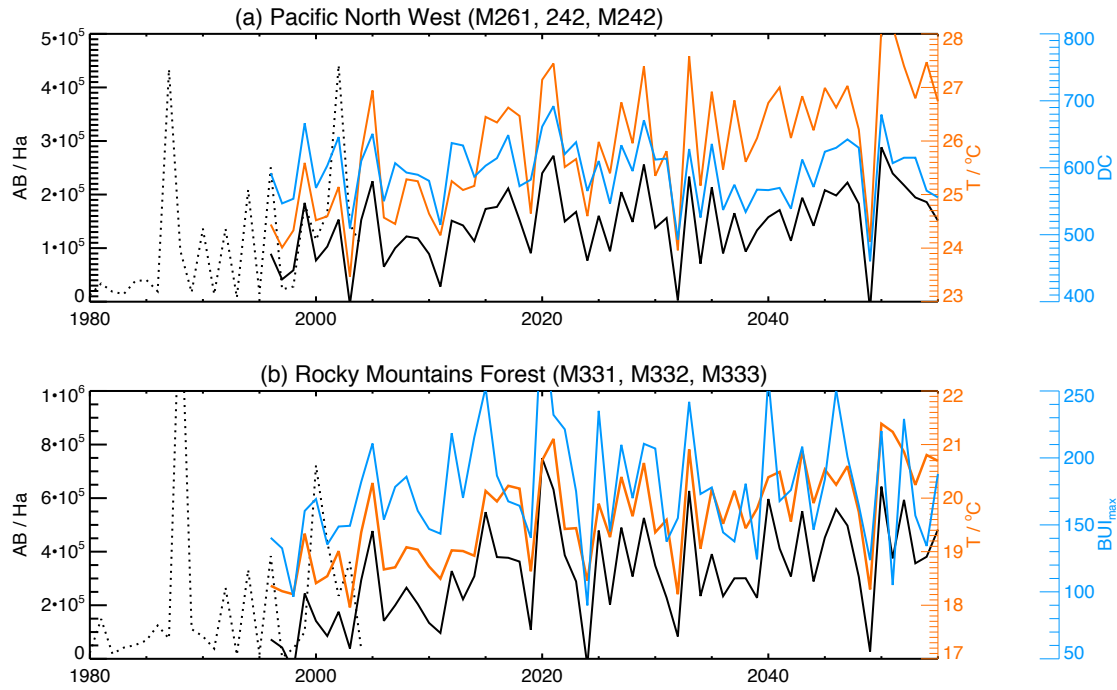


Figure 5. Annual area burned and May-October values of predictors used in regression equations for (a) Pacific Northwest and (b) Rocky Mountain Forest ecoregions between 1980 and 2055. Observed area burned (dotted black line) and predicted area burned (solid black line). Temperature (red) and drought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

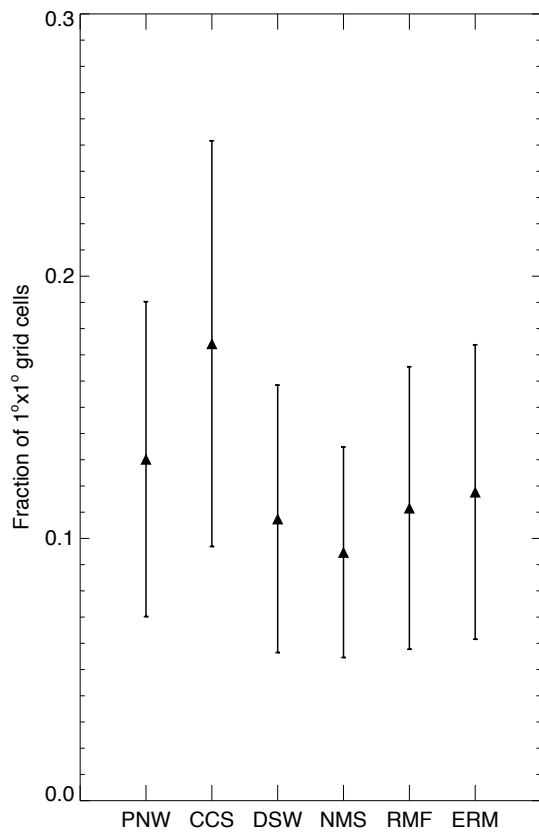


Figure 6. Fraction of $1^{\circ}\times 1^{\circ}$ grid squares (mean - solid symbols, error bars one standard deviation) within each ecoregion that contain 70% of area burned in any year calculated for the period 1980-2004. Ecoregions are as follows PNW, Pacific Northwest; CCS, Californian Coastal Shrub;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

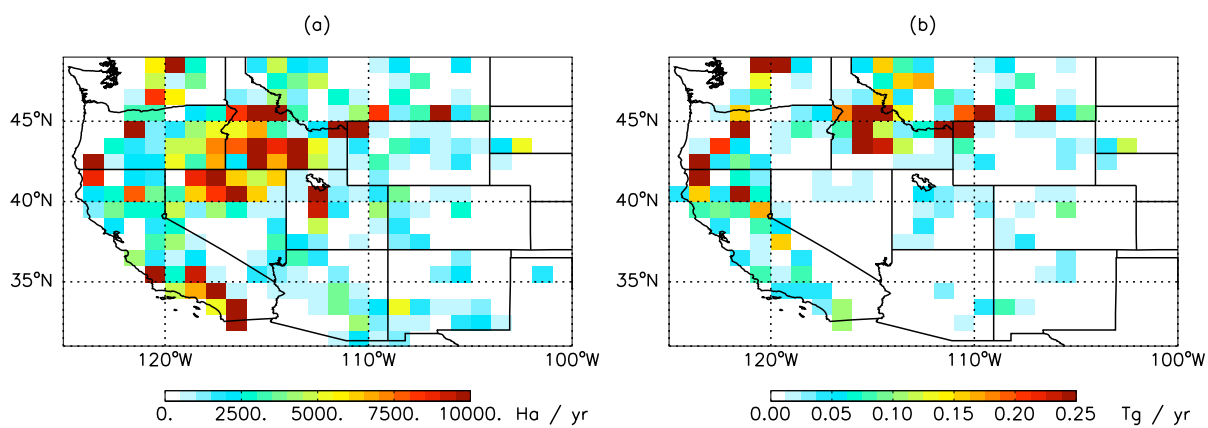


Figure 7. Annual mean (a) observed area burned and (b) dry biomass consumption for the period 1980-2004.

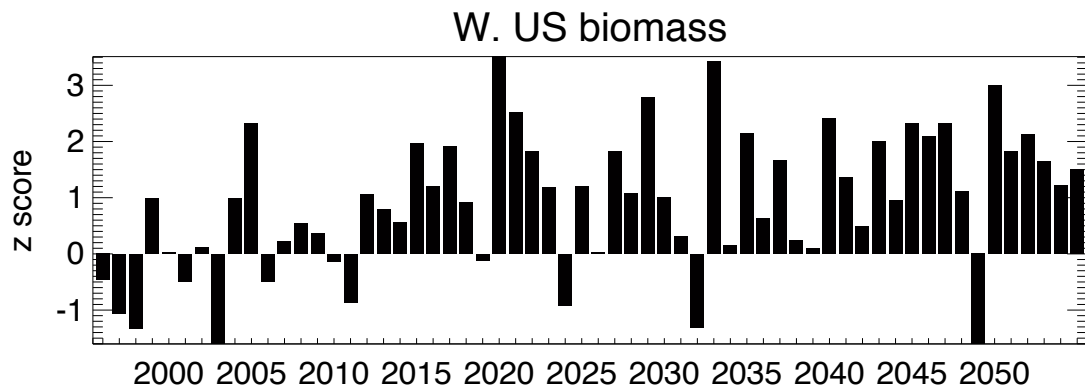


Figure 8. Predicted dry biomass consumption by wildfires in the western United States between 1996 and 2055 shown as a z-score, or standardized departure (the number of standard deviations away from the 1996-2005 mean).

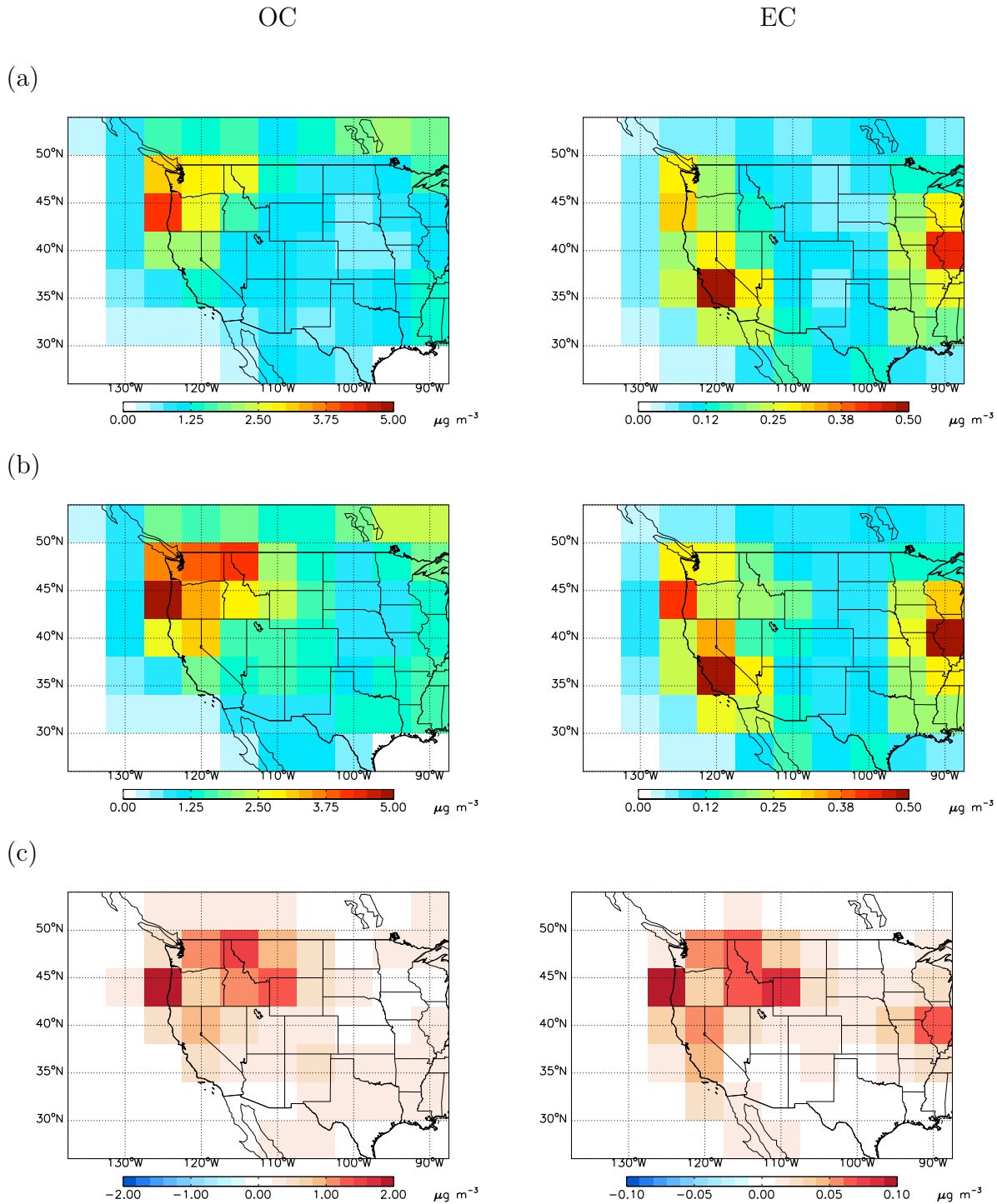
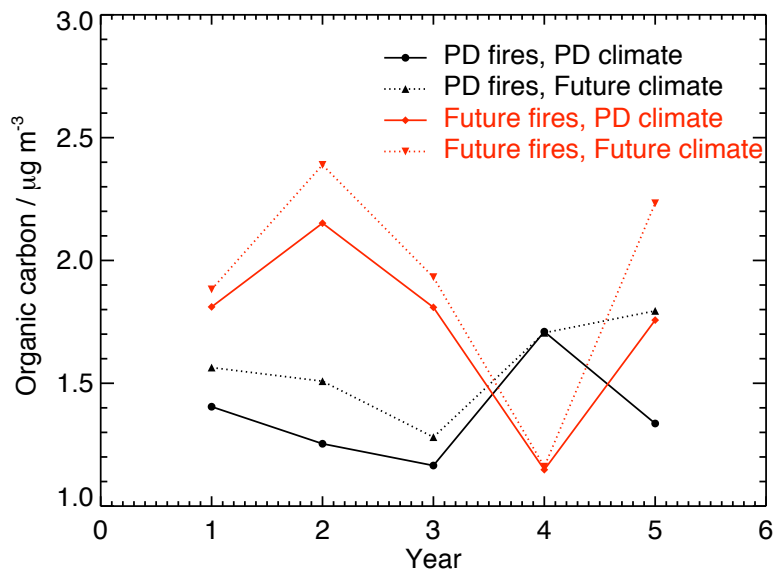


Figure 9. Simulated summertime (June-August) mean surface OC (left hand panels) and EC (right hand panels) concentrations over the western United States during (a) 1996-2000 and (b) 2046-2050. (c) The difference between simulated concentrations in 2046-2055 and 1996-2005. Units are $\mu\text{g m}^{-3}$.

(a)



(b)

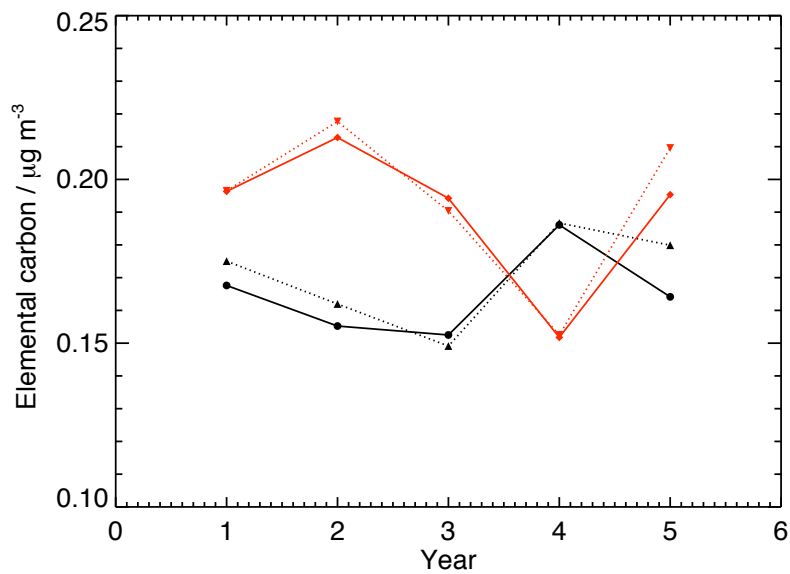


Figure 10. Simulated summertime average (June–August) surface concentrations of (a) OC and (b) EC in the western United States (31° – 49° N, 125° – 100° W) for (1) Present day (PD) wildfires (1996–2000) and present day climate (black circles), (2) Present day wildfires and future (2046–2050) climate (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%	$= -3.1 \times 10^6 + 9.4 \times 10^4 T + 1.7 \times 10^3 DC$
Californian Coastal Shrub	262, M262 261	635	32	24%	$= -3.6 \times 10^6 + 3.4 \times 10^4 T_{max} + 2.6 \times 10^4 FFMC$
Desert South West	322,321, M313,313	1600	61	49%	$= -1.64 \times 10^6 + 6.3 \times 10^4 T + 296 DC_{max}$
Nevada-Mtns/ Semi-desert	341, M341, 342	1740	22	37%	$= 3.9 \times 10^5 + 1.2 \times 10^4 FWI_{max} - 1.4 \times 10^6 Rain$
Rocky Mtns. Forest	M331, M332, M333	1760	60	48%	$= -6.55 \times 10^6 + 3.2 \times 10^5 T + 5.3 \times 10^3 BUI_{max}$
E. Rocky Mtns./ Great Plains	331,315	1300	8	57%	$= -3.6 \times 10^5 + 3.4 \times 10^4 DSR$

^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 Moisture 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 $\pm 1\sigma$ by ecoregion in the western United States

Ecoregion	Area burned / 10^5 ha			Ratio (F)/ (PD)	Stand. Depart. ^a	Slope ^b $\pm 1\sigma$ (ha yr ⁻¹)	P-value for slope
	Observed	Predicted					
	1980- 2004	1996- 2005- (PD)	2046- 2055 (F)				
Pacific North West	1.08 \pm 0.39	1.08 \pm 0.70	1.92 \pm 0.79	1.78	1.23	1440 \pm 470	<0.01
California Coastal Shrub	0.59 \pm 0.17	0.60 \pm 0.43	0.84 \pm 0.31	1.38	0.61	320 \pm 310	0.15
Desert South West	0.74 \pm 0.14	0.81 \pm 0.22	1.16 \pm 0.18	1.43	1.42	690 \pm 160	<0.01
Nevada Mtns/Semi-desert	2.84 \pm 0.71	3.04 \pm 1.03	3.14 \pm 0.67	1.03	0.13	-140 \pm 590	0.41
Rocky Mountain Forest	2.07 \pm 0.71	1.53 \pm 1.52	4.19 \pm 1.76	2.75	1.44	5010 \pm 1220	<0.01
E. Rocky Mnts/Great Plains	0.78 \pm 0.26	0.55 \pm 0.85	0.50 \pm 0.67	0.91	-0.07	-400 \pm 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		Standardised departure ^b	p-value ^c	% contribution ^d
	1996-2005	2046-2055			
Pacific North West					
DC	595	605	0.2	0.7	10
T / °C	24.9	26.9	1.7	<0.01	90
California Shrub					
T _{max} / °C	37.7	39.2	1.1	<0.01	95
FFMC	90.4	90.5	0.1	0.90	5
Desert South West					
T / °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 / °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.

Ecoregion	Annual mean biomass consumption / Tg			p-value ^a
	Observed 1980-2004	Simulated 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.