Response to Referee #1

We thank the referee for this helpful and comprehensive review, which has improved the manuscript. Detailed point-by-point responses to the reviewer comments are provided below. The reviewers' comments are shown in black with our responses marked as blue. The line numbers below refer to the revised manuscript to be submitted separately.

This paper describes the development of regressions that predict area burned in Wildland fires in Canada and Alaska. The authors use meteorological variables to drive these relationships for 13 ecosystems in northern North America. These relationships were then used to derive burned areas and further, emissions for current and future (mid-2000) conditions from an ensemble of 13 climate models. The resulting emissions were combined with emissions from the US (presented in prior work by the author) and used as inputs to chemical transport models that predict ozone concentrations.

Overall, this paper is well written. The material presented is appropriate for AC&P, and the results are relevant for those considering future air quality in North America (and beyond). The methods for development of the meteorology/area burned regressions are robust and I think extremely valuable. However, I do have some concerns about the use of the burned areas to develop emission estimates and how these were used to predict resulting air quality impacts. I don't think any of this is too major, but I would like to see these addressed before the paper is accepted.

General Comments:

The authors use emission factors from Andrea and Merlet (2001) to develop emission rates from the burned area estimates. These composite emission factors have been since updated (i.e., M.O. Andrea has available an updated list available to researchers, Akagi et al. (2011) has since published emission factors, Urbanski et al. has published emission factors for North America). Although I don't believe that the inclusion of more updated emission factors will not make a tremendous impact on the resulting model output, I think it is worthwhile to include the updates in this modeling.

→ The reviewer makes a good suggestion. We now compare fire emissions calculated with emission factors from Akagi et al. (2011) and Urbanski (2014) to those used in this study in a new Table S6. We performed two additional simulations with fire emissions calculated using emission factors from Akagi et al. (2011) (Table 1). We plotted a new Figure S3 showing the differences in the simulated ozone perturbations due to the discrepancies in emission factors. We quantified that simulations with emission factors from Akagi et al. (2011) project ozone increases of 5.5 ppbv in Alaska, 3.2 ppbv in Canada, and 0.9 ppbv in the western U.S. by future wildfire emissions. These enhancements are 14-23% higher than our previous estimates with emission factors from Andreae and Merlet (2001). In the revised paper, we have added the following explanations, analyses, and discussion.

In section 2.7:

"The emission factors from Andreae and Merlet (2001) have recently been updated by Akagi et al. (2011) and Urbanski (2014). As a check, we compare the predicted fire emissions using all three sets of emission factors (see Table S6 and related discussion in Section 3.3)." (Lines 383-386)

In section 2.8:

"Finally, we perform another two sets of simulations, one for present day (FULL_PD_EF) and the other for midcentury (FULL_A1B_EF), both of which use emission factors from Akagi et al. (2011), to estimate the modeling uncertainties due to emission factors." (Lines 457-460)

"We calculate the differences between FULL_PD_EF and FULL_PD to quantify the present-day uncertainties due to the emission factors, and the differences between FULL_A1B_EF and FULL_A1B to quantify these uncertainties at midcentury." (Lines 468-471)

In section 3.3:

"Estimates of fire emissions depend on emission factors. Using the same biomass burned calculated with observed area burned, we calculate three different sets of emissions using the factors from Andreae and Merlet (2001) (except for NO, see Table S3) Akagi et al. (2011), and Urbanski (2014) (Table S6). These emissions show similar magnitudes in CO and NH₃, but some differences in NO_x and non-methane organic compounds (NMOC). For example, NO_x from Akagi et al. (2011) is higher by 30-50% than that in Urbanski (2014) and in Table S3. Meanwhile, NMOC from Andreae and Merlet (2001) is lower by 20% than that in Akagi et al. (2011) and Urbanski (2014). In the following simulations and analyses, we use emission factors from Andreae and Merlet (2001) (except for NO from Table S3) and discuss the modeling uncertainties due to the application of different emission factors." (Lines 688-698)

In section 3.4:

"Our estimate of future fire impacts depends on the emission factors we adopted. Using emission factors from Akagi et al. (2011), we calculate larger fire-induced ozone enhancements at both present day and midcentury (Figure S3). As a result, simulations with emission factors from Akagi et al. (2011) project ozone increases of 5.5 ppbv in Alaska, 3.2 ppbv in Canada, and 0.9 ppbv in the western U.S. due to future wildfire emissions. These enhancements are 14-23% higher than our previous estimates with emission factors from Andreae and Merlet (2001) and Table S3." (Lines 737-744)

In section 4:

"First, the emission factors of ozone precursors are not well constrained, especially for NO_x . Sensitivity tests with emission factors from Akagi et al. (2011) show 14-23% higher fire-induced ozone than that with emission factors from Andreae and Merlet (2001) and the NO_x emission factor derived from an ensemble of experiments (Table S3). Using aircraft data from boreal fires, Alvarado et al. (2010) determined an emission factor of 1.1 g NO kg DM⁻¹, lower than our value of 1.6 g NO kg DM⁻¹ and much lower than the estimate of 3.0 g NO kg DM⁻¹ for extratropical forest fires in Andreae and Merlet (2001). Alvarado et al. (2010) found that 40% of wildfire NO_x is rapidly converted to PAN and

20% to HNO_3 and his estimate of 1.1 g NO kg DM^{-1} for fresh emissions includes these two species." (Lines 838-847)

I would have liked to have more details about the model simulations. Was plume rise included? What emissions (anthropogenic) were included in the simulations?

\rightarrow We have clarified as follows:

"The GEOS-Chem model is not coupled with a plume model, and as a result cannot simulate the impacts of plume rise. As in Leung et al. (2007), we emit 20% of emissions in each grid square to the model levels between 3 and 5 km and leave the rest in the boundary layer, as observations have shown that over 80% of plumes from North America fires are located in the boundary layer (Val Martin et al., 2010)." (Lines 434-438)

"Anthropogenic emissions for ozone precursors, including NO_x, CO, and non-methane VOCs, are as described in Table 1a of Wu et al. (2008) and are summarized here for completeness and transparency. Global emissions of NO_x and CO are upscaled from the $1^{\circ}\times1^{\circ}$ Emissions Database for Global Atmospheric Research (EDGAR) version 3 (Olivier and Berdowski, 2001). Anthropogenic VOC emissions are derived from the Global Emission Inventory Activity (GEIA) (Benkovitz et al., 1996). Over the North American domain, these global emissions are replaced with the EPA National Emissions Inventory (NEI) 2005 inventory (<u>http://www.epa.gov/</u>)." (Lines 405-412)

The authors model ozone concentrations with a global model (GEOS-chem) that includes a very coarse resolution (4x5 degrees). Further, the emissions input to the model are, I assume, included evenly across the month. While I agree that it is pretty much impossible to predict day to day fire variability in the modeling, I worry that this really dampens the impact on air quality. The authors include only one sentence about this uncertainty in the discussion of the manuscript (lines 796-799) and state that the model may underpredict pollution episodes (line 386). Therefore, I believe that the model results of MDA8 O3 don't have too much meaning.

 \rightarrow We agree that the use of coarse spatial and temporal resolution increases the uncertainties in the prediction of ozone air quality. In the discussion session, we extend our discussion as follows:

"Second, we estimated fire-induced O_3 concentrations using monthly emissions, due to the limits in the temporal resolution of predicted area burned. Such an approach may have moderate impacts on the simulated O_3 ; Marlier et al. (2014) found <1 ppb differences in surface $[O_3]$ over North America between simulations using daily and monthly fire emissions. The same study also predicted <10% differences in the accumulated exceedances for MDA8 O_3 globally. Third, the projections were performed at coarse spatial resolution of 4°×5°. As shown in Zhang et al. (2011), however, mean MDA8 O₃ in a nested grid simulation $(0.5^{\circ} \times 0.667^{\circ})$ is only 1-2 ppbv higher than that at $2^{\circ} \times 2.5^{\circ}$ resolution in the GEOS-Chem model. Fiore et al. (2002) reached a similar conclusion in comparing simulations at $4^{\circ} \times 5^{\circ}$ and $2^{\circ} \times 2.5^{\circ}$. They found that the coarse model resolution smoothed the regional maximum, resulting in a more conservative estimate of the intensity of pollution episodes." (Lines 868-879)

The authors report summertime mean and also MDA8 O3 values. In the discussion section, it is not always clear which they are discussing.

\rightarrow We have clarified that (section 3.4):

"Daily maximum 8-hour average (MDA8) surface ozone is a metric used by the U.S. Environmental Protection Agency (EPA) to diagnose ozone air quality. In this study, we use MDA8 ozone instead of daily mean ozone for all the analyses and discussion." (Lines 713-715)

Are modeled nighttime values included the monthly means, or is only daytime ozone concentrations considered? And how well does the model simulate nighttime and how does that impact the results.

→ We use MDA8 ozone instead of daily mean ozone for all the analyses and discussion. We focus on MDA8 ozone because it is a metric used by the U.S. Environmental Protection Agency (EPA) to diagnose ozone air quality. Both daytime and nighttime values are used in the calculation. MDA8 ozone typically occurs in daytime (Bloomer et al., 2010), when temperature is high, photolysis is rapid, and some natural (such as wildfires) and anthropogenic (such as vehicle) emissions are large. Challenges in simulating nighttime ozone would therefore have a negligible impact on our conclusions.

Evaluations of GEOS-Chem model have been performed extensively in previous studies. We have added the following sentences to the text:

"The simulated daily and monthly ozone concentrations from the GEOS-Chem model driven with meteorological reanalyses have been widely validated with site-level, aircraft, and satellite observations (Fiore et al., 2002; Wang et al., 2009; Alvarado et al., 2010; Zhang et al., 2011). Monthly mean ozone concentrations simulated with GISS meteorology have been evaluated by comparison with climatological ozonesonde data and reproduces values throughout the troposphere usually to within 10 ppbv (Wu et al., 2007). In addition, simulated daily ozone with GISS meteorology reasonably reproduces the summertime temporal variability of ozone concentrations as well as the pollution episodes in U.S. (Wu et al., 2008)." (Lines 396-404)

Finally, do the model simulations include the feedbacks of the aerosols emitted from these fires? The aerosols emitted from fires will have important impacts on the photolysis, meteorology, and even biogenic emissions that can all impact the predicted ozone concentrations. And if not, is the magnitude of the changes in ozone described in

this paper significant compared to the impact of these aerosol effects?

 \rightarrow GEOS-Chem includes the feedbacks of aerosol-induced light absorption on ozone phtotolysis, but not the feedbacks on meteorology or biogenic emissions. We now clarify in the text:

"In calculating photolysis rates within the plume, the model takes into account the attenuation of solar radiation by fire aerosols. This calculation has some importance; in their model study, Jiang et al. (2012) found that fire aerosols alone could reduce ozone concentrations by up to 15% close to the source due to the light extinction." (Lines 438-442)

Other minor comments:

Section 2.2: Is there a minimum fire size reported in the FAMWEB and the Canadian National Fire Database?

→ Yes. We now clarify the size of fires in these databases: For FAMWEB, "The minimum area burned is 1 ha and the maximum is 2.5×10^5 ha for the Inowak Fire, which began on June 25^{th} , 1997." (Lines 160-162) For NFDB, "The minimum area burned is 0.1 ha and the maximum is 6.2×10^5 ha for a fire that began on July 12^{th} , 1981." (Lines 177-178)

Section 2.4: Was some of the burn area data withheld from the regression analysis and then used to check the robustness of the regression results?

 \rightarrow The reviewer makes a good suggestion. We now report the results of a cross-validation test:

"We cross validate all the regressions with the leave-one-out approach following Littell et al. (2009). We calculate the ratio of the predicted residual sum of squares (PRESS) root mean square error (RMSE) to the standard deviation (SD) of area burned in each ecoregion as an indicator of the leave-one-out prediction error. A robust regression usually has the RMSE/SD ratio lower than 2 (Littell et al., 2009)." (Lines 234-239)

"The leave-one-out cross validation shows RMSE/SD ratios between 0.53-1.1 in boreal ecoregions (Table 4), suggesting that the prediction error is usually smaller than the variability of data. In a comparable study, Littell et al. (2009) calculated cross-validated RMSE/SD ratios of 0.56-2.08 for area burned in western U.S. ecoregions during 1977-2003. Our prediction shows much lower RMSE/SD ratios, indicating that the derived regressions (Table 4) are reasonably robust for the future projections." (Lines 503-508)

Section 2.5: What is the horizontal resolution of the climate model outputs? Did these have to be scaled down?

→ The horizontal resolution of these climate models has been listed in Table S1. We did not interpolate these model outputs to the uniform grid squares. Instead, we calculate the averages in each ecoregion by aggregating all available grids in the same ecoregion. We perform such aggregation for output of each climate model independently. We reproduce below the original text.

"We aggregate all of the climate simulations into ecoregions for the projection."

Line 257: Should be "We aggregate all of the climate simulations . . ."

 \rightarrow Corrected as suggested.

Lines 321-323: The authors made a comparison as a check. How did it look?

 \rightarrow We have reported the results from this comparison. In the third paragraph of section 3.3 and Table 4, we compare the derived fuel consumption from the two different approaches:

"In a sensitivity test, we derive fuel consumption with regional DC thresholds based on ecoregion-specific probability distributions. This approach reduces western fuel consumption by 8-16%, but increases eastern values by 2-37% (Table 4). It also predicts lower Alaskan fuel consumption compared with other studies. The boreal biomass burned calculated with this alternative approach is about 156.2 Tg DM yr⁻¹ for 1980-2009, almost identical to that estimated using a single probability distribution to define the DC thresholds (Figure 8a)." (Lines 669-676)

We have added a reference to the above results to clarify:

"As a check, we also compare the fuel consumption derived in this way with that calculated based on the ecoregion-specific DC thresholds (see Table 4 and related discussion in Section 3.3)." (Lines 327-329)

Lines 338-340: Just to clarify, the month of a fire is assumed to be the month in which the start date occurs?

 \rightarrow Yes, we have clarified as follows: "Area burned is assigned to the start month, as end dates are often uncertain (Kasischke et al., 2011)."

Lines 365-370: Why were more updated emission factors used in the simulations? (i.e., M.O. Andreae has an updated list from the 2001 paper; Akagi et al. (2011 and updates) are available, Urbanski 2014 is available, http://www.firelab.org/project/emission-factor-database). Although the changes aren't terribly large, there is a lot of updates to the emission factors available. Also, if NO contributes 30% of the fire-induced NOx, then why is the NOx emitted as NO? Shouldn't NO2 and other nitrogen species be included

(especially at such a coarse horizontal model resolution). How were the VOCs speciated? What specific compounds were included in the emissions?

→ As we have explained in our response to the general comment, we have performed two additional sensitivity tests to quantify the uncertainties due to emission factors in the revised manuscript. For NO_x emissions, we use NO as a unit for the emission, similar to the treatment in previous studies (e.g., Andreae and Merlet, 2001; Akagi et al., 2011; Urbanski, 2014). Because NO and NO₂ are in rapid photochemical equilibrium, GEOS-Chem can calculate the equilibrium NO_x concentrations with the initial emissions of NO. For VOC emissions, we now explain that the following specific compounds were included in the simulation: CH₄, C₂H₆, C₃H₆, C₃H₈, C₄H₈, C₅H₁₀, HCHO, C₂H₄O, C₃H₆O, and C₄H₈O (Table S6).

Lines 379-392: The authors here discuss the ability of the model to represent ozone concentrations in the atmosphere. However, it is unclear if they are referring to hourly, daily or monthly concentrations. This should be made clear.

 \rightarrow We have clarified in the text as follows:

"The simulated daily and monthly ozone concentrations from the GEOS-Chem model driven with meteorological reanalyses have been widely validated with site-level, aircraft, and satellite observations (Fiore et al., 2002; Wang et al., 2009; Alvarado et al., 2010; Zhang et al., 2011). Monthly mean ozone concentrations simulated with GISS meteorology have been evaluated by comparison with climatological ozonesonde data and reproduces values throughout the troposphere usually to within 10 ppbv (Wu et al., 2007). In addition, simulated daily ozone with GISS meteorology reasonably reproduces the summertime temporal variability of ozone concentrations as well as the pollution episodes in U.S. (Wu et al., 2008)." (Lines 396-404)

Line 400: The MEGAN v2.1 reference should be updated to Guenther et al., GMD, 2012

 \rightarrow Corrected as suggested.

Lines 409-418: What is the temporal resolution of the fires? Are the monthly values emitted evenly throughout the month? Or were they assigned differing daily or diurnal emission rates?

 \rightarrow We use monthly fire emissions because fire predictions on the daily scale are not available. The monthly values are distributed evenly throughout the month, without daily and diurnal variability.

"Second, we estimated fire-induced O_3 concentrations using monthly emissions, due to the limits in the temporal resolution of predicted area burned. Such an approach may

have moderate impacts on the simulated O_3 ; Marlier et al. (2014) found <1 ppb differences in surface $[O_3]$ over North America between simulations using daily and monthly fire emissions. The same study also predicted <10% differences in the accumulated exceedances for MDA8 O_3 globally." (Lines 868-873)

Line 420: Future ozone will also be impacted by changes in anthropogenic emissions, too.

 \rightarrow Yes. The interactions between the anthropogenic and wildfire emissions have large impacts on the future ozone. We clarify as follows:

"Surface ozone concentrations in the 21st century will be influenced not just by trends in wildfire emissions, but also by changes in atmospheric transport, temperature, cloudiness, wet and dry deposition, and natural/anthropogenic emissions." (Lines 443-445)

However, for the model simulations, we kept anthropogenic emissions "constant at the level of the year 2000 for both present day and future simulations, to isolate the effects of changes in biomass burning emissions."

Lines 482 and 484: replace "which" with "that"

 \rightarrow Corrected as suggested.

Response to Referee #2

We thank the referee for the helpful and comprehensive review, which has improved the manuscript. Detailed point-by-point responses to the reviewer comments are provided below. The reviewers' comments are shown in black with our responses marked as blue. The line numbers below refer to the revised manuscript to be submitted separately.

The manuscript by Yue et al. examines the changes in burned area caused by forest fires in the mid-century over Alaska, Canada, and the US, using a regression-based method. Resulting effects on ozone air pollution are also investigated. For both burned area and for air quality, the effects are found to be strongest in Alaska and western Canada, but also substantial in the rest of Canada and the US.

The manuscript, which nicely builds on the authors' previous work focusing on the western US, is a very useful addition to the literature, as it is the first work to provide such future estimates using output from multiple climate models as meteorological input. It is well written, and the methodology is well described. I certainly find it suitable for publication in ACP, following some minor corrections that I suggest below.

GENERAL COMMENTS:

- My impression after reading the manuscript was that the authors downplayed the importance of pollution effects of fires in Alaska and western Canada. Aside from the (sparse) population in those regions that is exposed to fire-generated pollution, would more ozone not be harmful for the ecosystems of the region as well? If so, I would suggest that the authors discuss this in the Discussion and Conclusions section.

→ Yes. Ozone has large impacts on the health and carbon uptake of ecosystems. A recent study by Pacifico et al. (2015) showed that fire-induced ozone may decrease carbon uptake in Amazon forest by a magnitude comparable to the total carbon emissions from the same fires, suggesting doubled fire emissions by including the ozone vegetation damage. The lead author of the paper under review has also investigated ozone damage to carbon assimilation in U.S. (Yue and Unger, 2014). In the future, we plan to further explore the ecosystem responses to fire-induced ozone in North America.

We emphasize the importance of ecosystem responses to fire-induced ozone in the last two sentences of this study:

"The regional perturbation of summer ozone by future wildfires can be as high as 20 ppbv over boreal forests, suggesting large damage to the health and carbon assimilation of the ecosystems (Pacifico et al., 2015). Using a newly developed model of ozone vegetation damage (Yue and Unger, 2014), we plan to explore the response of boreal ecosystems to fire-induced ozone enhancements." (Lines 889-893)

- I feel slightly uneasy with the 1981-1999 period being referred to as "present day". I suggest that the authors explain why it is acceptable to use this term for a somewhat

earlier period (which is centred at around 1990).

 \rightarrow We clarify our choice to specify 1981-1999 as the present-day.

"We use the output from the 20C3M scenario for the prediction of area burned in the present day (1981-1999). Simulations in the CMIP3 ensemble for the years beyond 1999 (or in some cases 2000) are driven by a suite of future greenhouse gas scenarios, making comparison with observations difficult." (Lines 252-256)

SPECIFIC COMMENTS:

Page 13869, Lines 1-2: Please rephrase to avoid implying that these are the only important emissions from North American wildfires.

 \rightarrow We have rephrased this sentence as: "North American wildfires are important sources of air pollutants, such as ozone precursors ...".

Page 13869, Lines 14-20: These would fit better towards the end of the introduction section (though some of it is repeated anyway).

 \rightarrow We have removed these sentences in the revised manuscript.

Page 13871, Line 3: Please add "in the scenario used" after "concentrations".

 \rightarrow Added as suggested.

Page 13874, Line 23: Is "also" needed here?

 \rightarrow We used "also" to indicate that site-level observations have been used in two ways. First, they were used to calculate monthly averages in ecoregions (as explained in the sentence before this line). Second, they were used as the input for the Canadian Fire Weather Index system.

Page 13875, Lines 14-16: I do not find it entirely clear how the 44 and 132 terms arise. Perhaps this paragraph could be more explanatory in that respect.

 \rightarrow We now explain the number of predictors more clearly as follows:

"We calculate the means of five meteorological variables (mean and maximum temperature, relative humidity, precipitation, and 500 hPa geopotential height) over six different time intervals (winter, spring, summer, autumn, annual, and fire-season),

making 30 meteorological predictors in all. The mean and maximum values of the seven daily CFWIS indices during fire season are also included in the regressions, making another 14 fire-index predictors. As a result, a total of 44 terms is generated for the current year. As in Yue et al. (2013), we also employ all these variables from the previous two years in the regression, making 132 (44×3) potential terms for the regression." (Lines 220-228)

Page 13876, Lines 15-17: Is this scaling used for the future too? That should be clarified here.

→ Yes. We have clarified it as follows: "In order to reduce model bias, we scale the aggregated variables of both present day and future from each GCM using the mean observations for 1980-2009 from the GSOD sites." (Lines 263-265)

Page 13877, Line 8: "US. FCCS" - There seems to be a typo here.

 \rightarrow Yes. We have removed 'US.' to correct it.

Page 13878, Line 28: Please add "per unit area burned" after "consumption".

 \rightarrow Added as suggested.

Page 13881, Line 22: It might be better to use "yr⁻¹" or "year⁻¹" instead of "a⁻¹", as it is more conventional.

 \rightarrow We have replaced all the 'a⁻¹' to 'yr⁻¹' in the text, as well as that in the Figure 3.

Page 13882, Lines 3-4: Is the 20% of emissions released above the boundary layer occurring for specific meteorological conditions, or randomly? Please specify.

→ Plume height is driven by the fire dynamical heat flux (related to active fire area and sensible heat flux) and atmospheric conditions (such as stability). The current GEOS-Chem model does not include a plume model to simulate such impacts. As an alternative solution, "As in Leung et al. (2007), we emit 20% of emissions in each grid square to the model levels between 3 and 5 km and leave the rest in the boundary layer, as observations have shown that over 80% of plumes from North America fires are located in the boundary layer (Val Martin et al., 2010)." (Lines 435-438)

Page 13882, Line 16: Please add "additionally" between "we" and "implement".

 \rightarrow Added as suggested.

Figure 3: Please briefly remind the reader (in the caption) where the observations come from.

→ We have added the following information in the caption of Figure 3: "Observations are compiled using fire reports from the Fire and Aviation Management Web Applications (FAMWEB) for Alaska and those from the Canadian National Fire Database (CNFD) for Canada."

Figure 4: Please add "meteorological" before "observations" in the caption.

 \rightarrow Added as suggested.

Page 13885, Lines 2-5: I am not sure I understand – Table 2 suggests that 500 geopotential heights are used extensively in the regressions, but this sentence implies that they are not. What is the case?

 \rightarrow Geopotential height anomalies have been selected as predictors in most of ecoregions, except for some areas in central and eastern Canada. We have clarified the text as follows:

"However, in some of the central and eastern Canadian ecoregions (e.g. Taiga Plain and Eastern Taiga Shield), such height anomalies are not selected as terms in our regressions (Table 2). Although geopotential height may still influence wildfire activity in those areas, this variable tends to correlate with fire weather indices or moisture variables. We attempt to avoid collinearity in our regressions, and so geopotential height may not be selected as a predictor there." (Lines 533-538)

Figure 5: Please add a parenthesis indicating "(midcentury/present-day)" or something similar above the bottom panel, for clarity.

 \rightarrow Added as suggested.

Page 13886, Line 4: Yes, but please provide a reference for the "a common problem in GCMs" statement.

 \rightarrow We have added the reference of Mearns et al. (1995) to support the statement.

Page 13887, Lines 19-20: Can you explain why there is this different behaviour between

western and eastern parts of the region?

 \rightarrow We have clarified the text:

"In the Western Taiga Shield, where area burned is projected as a function of the fire index ISI (positive relationship, Table 2) and relative humidity, the median area burned shows a small, insignificant decrease in the future atmosphere (Table 3, Figure 7b), because the increases of rainfall significantly reduce ISI there. In the Eastern Taiga Shield, where area burned is a function of the fire index DMC (negative relationship, Table 2) and relative humidity, the median area burned again shows an insignificant decrease by mid-century (Table 3, Figure 7b). DMC is related to both temperature and precipitation. Here rising temperatures enhance DMC and outweigh the effects of greater humidity (Table S4)." (Lines 609-617)

Page 13889, Line 16: Maybe the authors meant to write "overestimate" here?

 \rightarrow Yes. We have corrected the error.

Page 13891, Line 8: Please change "results" to "result".

 \rightarrow Corrected as suggested.

Page 13893, Line 15: Please add "for" before "all" and "we" before "calculate".

→ Added as suggested. The text reads: "... where for almost all GCMs we calculate significant increases in area burned ..."

Page 13894, Line 10: I would suggest explicitly stating whether the expected changes mentioned are increases or decreases (the latter, I presume). Also: Is it likely that dead vegetation may temporarily imply more flammable fuel?

 \rightarrow As the reviewer suggested, mountain pine beetle (MPB) may decrease fuel load, but meanwhile increase fuel flammability by decreasing fuel moisture (Simard et al., 2011). It is unclear whether these effects have the net positive or negative impacts on wildfire emissions at the large domain. Since a certain conclusion is beyond the scope of this study, we revise the sentence as follows:

"In addition, mountain pine beetle outbreaks are important disturbances for both boreal and U.S. forests, leading to changes in fuel load and fuel moisture with climatic shifts (Fauria and Johnson, 2009; Simard et al., 2011; Jenkins et al., 2014). We did not consider these effects in this study." (Lines 820-824)

Page 13894, Line 22: Suggest changing "of" to "from".

 \rightarrow Changed as suggested.

Page 13895, Line 8: Not every reader will be familiar with what the $\Delta O3/\Delta CO$ ratio is useful for, so please add a sentence to explain (perhaps with a reference).

→ This ratio is that observed within the plume, with delta indicating the enhancement over background for ozone with respect to CO (emitted directly from the fire). This has been standard practice dating at least since Wofsy et al. (1992).

We have clarified the text as follows:

"In their review, Jaffe and Wigder (2012) reported that increased ozone is observed in most plumes, but with huge variability in the enhancement ratio of $\Delta O_3/\Delta CO$ within the plume." (Lines 852-854)

Page 13895, Lines 17-20: Yes, but larger scale effects could become stronger with more PAN being formed.

 \rightarrow We now clarify our intent here:

"In any event, our use of a moderately high NOx emission factor and omission of rapid PAN formation within the plume may lead to an overestimate of fire-induced ozone in local areas (Alvarado et al., 2010)." (Lines 863-865)

Page 13895, Lines 20-22: The work of Marlier et al. (2014) suggests that at least the temporal resolution effect is minimal for ozone.

 \rightarrow We thank the reviewer for this suggestion and have modified the discussion as follows:

"Second, we estimated fire-induced O_3 concentrations using monthly emissions, due to the limits in the temporal resolution of predicted area burned. Such an approach may have moderate impacts on the simulated O_3 ; Marlier et al. (2014) found <1 ppb differences in surface $[O_3]$ over North America between simulations using daily and monthly fire emissions. The same study also predicted <10% differences in the accumulated exceedances for MDA8 O_3 globally. Third, the projections were performed at coarse spatial resolution of $4^{\circ}\times5^{\circ}$. As shown in Zhang et al. (2011), however, mean MDA8 O_3 in a nested grid simulation ($0.5^{\circ}\times0.667^{\circ}$) is only 1-2 ppbv higher than that at $2^{\circ}\times2.5^{\circ}$ resolution in the GEOS-Chem model. Fiore et al. (2002) reached a similar conclusion in comparing simulations at $4^{\circ}\times5^{\circ}$ and $2^{\circ}\times2.5^{\circ}$. They found that the coarse model resolution smoothed the regional maximum, resulting in a more conservative estimate of the intensity of pollution episodes." (Lines 868-879)

Reference

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Impact of 2050 climate change on North American wildfire:

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2	consequences for ozone air quality
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Abstract

19 We estimate future area burned in Alaskan and Canadian forest by the midcentury 20 (2046-2065) based on the simulated meteorology from 13 climate models under the A1B scenario. We develop ecoregion-dependent regressions using observed relationships 21 between annual total area burned and a suite of meteorological variables and fire weather 22 23 indices, and apply these regressions to the simulated meteorology. We find that for Alaska and western Canada almost all models predict significant (p < 0.05) increases in 24 area burned at the midcentury, with median values ranging from 150% to 390%, 25 depending on the ecoregion. Such changes are attributed to the higher surface air 26 temperatures and 500 hPa geopotential heights relative to present day, which together 27 lead to favorable conditions for wildfire spread. Elsewhere the model predictions are not 28 as robust. For the central and southern Canadian ecoregions, the models predict increases 29 in area burned of 45-90%. Except for the Taiga Plain, where area burned decreases by 30 31 50%, no robust trends are found in northern Canada, due to the competing effects of hotter weather and wetter conditions there. Using the GEOS-Chem chemical transport 32 model, we find that changes in wildfire emissions alone increase mean summertime 33 34 surface ozone levels by 5 ppbv for Alaska, 3 ppbv for Canada, and 1 ppbv for the western U.S. by the midcentury. In the northwestern U.S. states, local wildfire emissions at 35 midcentury enhance surface ozone by an average of 1 ppbv, while transport of boreal fire 36 37 pollution further degrades ozone air quality by an additional 0.5 ppbv. The projected changes in wildfire activity increase daily summertime surface ozone above the 95th 38 39 percentile by 1 ppbv in the northwestern U.S., 5 ppbv in the high latitudes of Canada, and 15 ppbv in Alaska, suggesting a greater frequency of pollution episodes in the future 40 41 atmosphere.

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Keywords wildfire, ensemble projection, ozone concentrations, boreal ecoregions,
pollution episodes, fuel consumption, fire emissions

45

46 1 Introduction

47 North American wildfires are important sources of air pollutants, such as ozone 48 precursors carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic 49 compounds (VOCs). Their emissions can strongly affect air quality locally and, in the 50 case of large fires, in areas thousands of kilometers downwind in the United States and Canada (Wotawa and Trainer, 2000; Morris et al., 2006; Kang et al., 2014), over the 51 52 mid-Atlantic (Val Martin et al., 2006; Cook et al., 2007), and in Europe (Real et al., 2007). Previous studies have projected increases in the area burned by North American 53 wildfire in the 21st century due mainly to warmer temperatures (Flannigan et al., 2005; 54 Balshi et al., 2009; Wotton et al., 2010; Price et al., 2013; Boulanger et al., 2014), 55 implying further degradation of air quality by wildfire emissions in a changing climate. 56 However, predicted increases in future precipitation in Alaska and Canada (Christensen 57 et al., 2007) may have an opposing effect on future wildfire activity, resulting in large 58 59 uncertainties in fire projections.

Wildfires in Canada and Alaska often have much larger size compared with those in 60 the contiguous United States (Stocks et al., 2002; Westerling et al., 2003). Emissions 61 from boreal wildfires can have significant effects on air quality over the contiguous U.S. 62 (Sigler et al., 2003; Miller et al., 2011; Kang et al., 2014). In the summer of 1995, 63 64 transport of forest fire emissions from northwestern Canada reached as far south as the central and southern U.S., increasing CO concentrations as much as 200 ppb in that 65 66 region (Wotawa and Trainer, 2000). The same fires also enhanced ozone in central and southern U.S. by 10-30 ppbv, most of which was associated with NO_x directly emitted by 67 the Canadian fires and the remainder with the oxidation of wildfire CO by locally emitted 68 NO_x (McKeen et al., 2002). The summer of 2004 was one of the most intense fire seasons 69 on record for Canada and Alaska (Turquety et al., 2007; Lavoue and Stocks, 2011). An 70 analysis of flight data over the northeastern U.S. concluded that boreal fire emissions 71 during that summer contributed 10% of the observed CO over the northern United States 72

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(Warneke et al., 2006) and enhanced mean summertime ozone there by 1-3 ppbv
(Hudman et al., 2009). Smoke plumes occasionally reached Houston that summer,
increasing ozone there as much as 30-90 ppbv between the surface and 3 km altitude and
likely contributing to violations of the 8-hr ozone air quality standard (Morris et al.,
2006).

92 Area burned in North America is influenced by fuel availability, weather, ignition, 93 and fire suppression practices. Many studies, however, have suggested that meteorology 94 is the single most important factor (Hely et al., 2001). For example, Gillett et al. (2004) 95 found that changes in temperature alone explain 59% of the variance of the observed area burned in Canada for 1920-1999. Regression studies using surface meteorological data 96 and fire indices also yield high R^2 of 0.4-0.6 for area burned in boreal ecoregions 97 (Flannigan et al., 2005). In addition to the surface weather conditions, the 500 hPa 98 geopotential height is also found to be important in predictions of area burned in boreal 99 100 forests (Skinner et al., 1999; Wendler et al., 2011), since this variable can indicate the occurrence of blocking highs over the continent, which cause rapid fuel drying (Fauria 101 102 and Johnson, 2008).

103 Studies examining climate impacts on wildfire activity in North America have 104 projected increases in area burned over most boreal ecoregions in the 21st century. 105 Flannigan and Van Wagner (1991) developed linear regressions between area burned and 106 fire indices. They applied these regressions with the mean climate simulated by three 107 general circulation models (GCMs) and projected an increase of 40% in Canadian area 108 burned in a doubled CO₂ atmosphere, relative to present day. Flannigan et al. (2005) 109 improved the previous projection with more complete meteorological station data, higher 110 spatial resolution, and a stepwise regression scheme with more potential regression 111 factors. Their results showed that area burned increases by 70-120% in boreal ecoregions by 2080-2100, a period with roughly tripled atmospheric CO₂ concentrations, in the 112 scenario used. However, Balshi et al. (2009) predicted that area burned in Alaska and 113

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115 Canada would double by 2050, a rate more rapid than in the projections by Flannigan et 116 al. (2005). The discrepancies among these studies arise in part from the differences in the 117 climate scenarios as well as the sensitivity of the particular GCMs to increases in 118 greenhouse gases.

In this study, we investigate the impact of changing climate on future Alaskan and 119 120 Canadian area burned and the consequences for ozone air quality in North America by 121 2046-2065 under a moderately warming scenario. Wildfires produce abundant ozone 122 precursors, and many, but certainly not all, observational studies of boreal fires suggest 123 subsequent ozone generation either locally or downwind (Jaffe and Wigder, 2012). We 124 build here on our earlier study (Yue et al., 2013), which projected future area burned in the western U.S. using stepwise regressions and the simulated climate from an ensemble 125 of climate models from the World Climate Research Programme's (WCRP's) Coupled 126 127 Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 128 2007a). Yue et al. (2013) predicted that the warmer and drier summer climate over the western U.S. at mid-century would increase area burned there by 60% and the consequent 129 130 biomass burned by 77%. Yue et al. (2013) further calculated regional increases of 131 46-70% in surface organic carbon aerosol and 20-27% in black carbon aerosol due to the 132 increased fire emissions. For this study, we focus on ozone air quality. We rely on the 133 CMIP3 ensemble of climate models to obtain confidence in projections of boreal area 134 burned, and we combine these results with those of Yue et al. (2013) for the western U.S. 135 Using the estimated fuel consumption and emission factors for ozone precursors, we 136 calculate future fire emissions over North America. Finally, we quantify the impacts of 137 those emissions on ozone mixing ratios at the midcentury, using the GEOS-Chem 138 chemical transport model (CTM) driven by the Goddard Institute for Space Studies 139 General Circulation Model 3 (GISS GCM3).

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141 2 Data and methods

142 2.1 Boreal ecoregions

We divide Alaskan and Canadian forests into 12 ecoregions (Figure 1), following the definitions of the Ecological Stratification Working Group (1996) with modifications by Stocks et al. (2002) and Flannigan et al. (2005). Area burned outside these ecoregions is small. In northern Canada cold weather and the lack of fuel continuity for the tundra and mountainous regions limits fire activity (Stocks et al., 2002), while regulations restrict agricultural burning in the southern part of central Canada.

149 We describe the 12 ecoregions as follows. Located in the central Alaska, the Alaska 150 Boreal Interior consists mainly of plains and hills and is covered with Arctic shrubs and 151 open coniferous forest. The Taiga Cordillera in western Canada has similar vegetation, although the higher elevation leads to lower temperatures. Three western ecoregions, the 152 Alaska Boreal Cordillera, the Canadian Boreal Cordillera, and the Western Cordillera are 153 154 located along the Rocky Mountains. The high elevation causes abundant precipitation, especially for the Western Cordillera, resulting in dense forests. In contrast, the two 155 central Canadian ecoregions, the Taiga and Boreal Plains, are at lower altitudes and are 156 157 characterized by tundra meadow and aspen forest. The Western Taiga Shield is a plain in 158 north central Canada characterized by shrub and conifer forests. The Hudson Plain, to the 159 south of Hudson Bay, is dominated by wetlands. Stocks et al. (2002) defined the Eastern Taiga Shield as covering most of northern Quebec. Here we redefine this ecoregion so 160 161 that it covers just the southwestern part, where ~90% of the area burned in the original 162 ecoregion occurs. We divide the Mixed Wood Shield, a large ecoregion in southeast 163 Canada, into eastern and western parts. Fire activity in these two subregions is significantly different (Flannigan et al., 2005). 164

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166 2.2 Fire data

We compile monthly $1^{\circ} \times 1^{\circ}$ area burned from 1980 to 2009 based on interagency fire reports. For Alaska, we use incidence reports managed by the National Wildfire

169 Coordinating Group from the Fire and Aviation Management Web Applications (FAMWEB, http://fam.nwcg.gov/fam-web/weatherfirecd/, downloaded on June 5th, 170 171 2012). Five agencies, the U.S. Forest Service (USFS), Bureau of Land Management 172 (BLM), Bureau of Indian Affairs (BIA), Fish and Wildlife Service (FWS), and National Park Service (NPS), provide ~5000 records of fire incidence in Alaska between 1980 and 173 174 2009. Each record documents the name, location (latitude and longitude), start and end 175 time, ignition source (lightning or human) and area burned of an individual fire. The minimum area burned is 1 ha and the maximum is 2.5×10^5 ha for the Inowak Fire, which 176 177 began on June 25th, 1997. Duplicates are expected because fires burn in lands managed by different agencies (Kasischke et al., 2011). We identify and delete duplicate records if 178 two or more fires have same names and areas, and occur within a distance of 50 km on 179 the same day. Thus we obtain a corrected subset and compare it with the annual fire 180 the National Interagency Coordination 181 report from Center (NICC, 182 http://www.nifc.gov/nicc/). NICC manages fire reports from federal agencies, states, and private ownership, and so has more complete datasets relative to FAMWEB. NICC, 183 184 however, provides annual total area burned only back to 1994. The correlation R between FAMWEB and NICC is 1.0 and the differences are within 2% for 1994-2009, giving us 185 186 confidence in our compilation of FAMWEB area burned. 187 For Canada, we use fire point data from the Canadian National Fire Database

188 (CNFDB, http://cwfis.cfs.nrcan.gc.ca/ha/nfdb), which is an extension of the Large Fire 189 Database (LFDB) summarized in Stocks et al. (2002). The database provides over 190 210000 records of forest fires during 1980-2009, collected from provinces, territories, 191 and Parks Canada. Each CNFDB record includes the name, location, size, and time of one fire. The minimum area burned is 0.1 ha and the maximum is 6.2×10^5 ha for a fire 192 193 that began on July 12th, 1981. Duplicates in CNFDB are much fewer, possibly because 194 the redundant records were deleted when the dataset was compiled into a Geographic Information System. Although the total number of fires is immense, only about 5% are 195

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199 greater than 100 ha. These large fires account for over 99% in area burned in the dataset, 200 as was the case for the LFDB.

201 We aggregate both the FAMWEB and CNFDB report data onto $1^{\circ} \times 1^{\circ}$ grids, based on 202 the location of fires. Area burned is assigned to the start month, as end dates are often 203 uncertain (Kasischke et al., 2011). The monthly gridded area burned is used to derive fire 204 emissions. To develop the fire models, we aggregate the fire report data into boreal 205 ecoregions across Alaska and the Canadian boreal forest (Figure 1) and then sum the area 206 burned within each ecoregion for the entire fire season (May-October) to reduce noise in 207 the regression.

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209 2.3 Meteorological data and fire weather indices

We use daily observations for 1978-2009 from the Global Surface Summary of the 210 211 Day dataset (GSOD, http://www.ncdc.noaa.gov/). The length of meteorological data is 212 two years longer than that of fire data, because the regressions employ terms that depend on the weather occurring up to 2 years before the area burned. The GSOD provides 18 213 daily surface meteorological variables for over 2000 stations in Alaska and Canada. We 214 215 select 157 sites within the 12 ecoregions that provide observations for at least two thirds 216 of the days during 1978-2009 (Figure 1). We use daily mean and maximum temperature, 217 total precipitation, and wind speed and calculate relative humidity using daily mean 218 temperature and dew point temperature. We also use the 500 hPa geopotential height 219 from the North American Regional Reanalysis (NARR, Mesinger et al., 2006). Both the 220 site measurements and the NARR reanalysis data are binned into ecoregions to derive 221 monthly averages.

222 The site observations are also used as input for the Canadian Fire Weather Index 223 system (CFWIS, Van Wagner (1987)). The CFWIS uses daily temperature, relative humidity, wind speed, and total precipitation to calculate three fuel moisture codes and 224 four fire severity indices. The fuel moisture codes indicate moisture levels for litter fuels 225

226 (Fine Fuel Moisture Code, FFMC), loosely compacted organic layers (Duff Moisture 227 Code, DMC), and deep organic layers (Drought Code, DC). The FFMC is combined with 228 wind speed to estimate the Initial Spread Index (ISI). The DMC and DC are used to 229 derive the Build-up Index (BUI) to indicate the availability of fuel. The ISI and BUI are then combined to create the Fire Weather Index (FWI) and its exponential form as the 230 231 Daily Severity Rating (DSR). The CFWIS indices have been widely used in fire-weather 232 research over North America (Amiro et al., 2004; Flannigan et al., 2005; Balshi et al., 233 2009; Spracklen et al., 2009), and in our previous work (Yue et al., 2013)

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235 2.4 Regression approach

We use total area burned during the fire season as the predictand, and we assume that 236 the influences of both topography and fuels on wildfire activity are roughly uniform 237 238 across each region. We calculate the means of five meteorological variables (mean and maximum temperature, relative humidity, precipitation, and 500 hPa geopotential height) 239 240 over six different time intervals (winter, spring, summer, autumn, annual, and 241 fire-season), making 30 meteorological predictors in all. The mean and maximum values 242 of the seven daily CFWIS indices during fire season are also included in the regressions, 243 making another 14 fire-index predictors. As a result, a total of 44 terms is generated for 244 the current year. As in Yue et al. (2013), we also employ all these variables from the 245 previous two years in the regression, making 132 (44×3) potential terms for the 246 regression.

We set up two criteria to select a factor as a predictor at each step. First, the chosen factor must have the maximum contribution to the *F* value, a metric for variance, of the predictand among the unselected factors. Second, this factor must exhibit low correlation with those already selected, with *p* value > 0.5. The first criterion produces a function with the largest possible predictive capability, while the second helps increase the stability of the function by introducing independent predictors (Philippi, 1993). We cross

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We calculate the ratio of the predicted residual sum of squares (PRESS) root mean square
error (RMSE) to the standard deviation (SD) of area burned in each ecoregion as an
indicator of the leave-one-out prediction error. A robust regression usually has the
RMSE/SD ratio lower than 2 (Littell et al., 2009).

In Yue et al. (2013), we also developed a parameterization for area burned in the western U.S. The parameterization was a function of temperature, precipitation, and relative humidity. The same functional form was applied throughout the domain, scaled by an ecoregion-dependent fire potential coefficient. We find that the parameterization approach fails in boreal forests, probably because the driving factors for wildfires vary greatly over the vast boreal areas.

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272 2.5 CMIP3 model data

273 We use daily output from 13 climate models in the CMIP3 archive (Meehl et al., 2007a) for the fire projection (Table S1). The variables we select include daily mean and 274 275 maximum temperature, total precipitation, and surface wind speed. We calculate daily 276 RH for the CMIP3 models using other archived meteorological variables. We also use the 277 monthly mean 500 hPa geopotential heights from all 13 GCMs. We use the output from 278 the 20C3M scenario for the prediction of area burned in the present day (1981-1999). 279 Simulations in the CMIP3 ensemble for the years beyond 1999 (or in some cases 2000) 280 are driven by a suite of future greenhouse gas scenarios, making comparisons with 281 observations difficult. For the future atmosphere (2046-2064), we use the simulated climate under the A1B scenario, which assumes a greater emphasis on non-fossil fuels, 282 283 improved energy efficiency, and reduced costs of energy supply. CO₂ reaches 522 ppm 284 by 2050 in this scenario (Solomon et al., 2007), resulting in a moderate warming relative to other scenarios (Meehl et al., 2007b). Over this relatively short timeframe, the A1B 285 scenario is consistent with two moderate scenarios in the newer Representative 286

287 Concentration Pathways, RCP 4.5 and RCP6.0 (Moss et al., 2010). We aggregate all of 288 the climate simulations into ecoregions for the projection. In order to reduce model bias, 289 we scale the aggregated variables of both present day and future from each GCM using 290 the mean observations for 1980-2009 from the GSOD sites. The changes in area burned 291 and meteorological variables are examined with a Student t-test and only those with p <292 0.05 are considered as significant.

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294 2.6 Fuel consumption

295 Fuel consumption is the amount of both live and dead biomass burned per unit area. It depends on both fuel load and burning severity. In Yue et al. (2013), we estimated fuel 296 load over the western U.S. using the 1 km dataset from the USFS Fuel Characteristic 297 Classification System (FCCS, http://www.fs.fed.us/pnw/fera/fccs/, McKenzie et al., 298 2007). The FCCS defines \sim 300 types of fuelbed based on the distribution of vegetation 299 300 types from the Landscape Fire and Resource Management Planning Tools (LANDFIRE, http://www.landfire.gov/). Each type of fuelbed consists of seven basic fuel classes (i.e., 301 302 light, medium, heavy fuels, duff, grass, shrub, and canopy) each with a different load 303 (Ottmar et al., 2007). Here, for Canada, we use the 1 km fuel type map from the Canadian 304 Fire Behavior Prediction (FBP) system, which is derived from remote sensing and forest inventory data and includes just 14 types (Nadeau et al., 2005). For Alaska, we use a fuel 305 306 map created by the USFS, which also follows the classification scheme of Nadeau et al. 307 (2005). However, the FBP system does not provide fuel load, and so we follow Val 308 Martin et al. (2012), who matched the Canadian FBP fuelbeds with their corresponding 309 types in the FCCS and in this way estimated the fuel load for both Canada and Alaska 310 (see their Table A1).

Burning severity indicates the fraction of fuel load burned by fires and varies by moisture state. We follow the approach of Val Martin et al. (2012), who used the USFS CONSUME model 3.0 (Ottmar, 2009) to calculate burning severity and the resulting fuel

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316 consumption for a given fuel load. In this approach, the derived FBP fuel loads are 317 applied to CONSUME, yielding reference fuel consumption for five moisture conditions: 318 wet, moist, moderately dry, dry, and extra dry (Val Martin et al., 2012). Here we use a 319 newer model version, CONSUME-python (https://code.google.com/p/python-consume/), 320 which fixes some errors in CONSUME 3.0. The updated reference fuel consumption for 321 different FBP fuel types and moisture states is given in Table S2. Our values for C3 322 (mature jack or lodgepole pine) and C5 (red and white pine) fuel types are 40-65% lower 323 than those in Val Martin et al. (2012), likely because of errors in the calculation of duff 324 fuel in CONSUME 3.0. We aggregate the new 1 km fuel consumption map to 1° 325 resolution to match that of gridded area burned. Figure 2a shows fuel consumption for moderately dry conditions. The figure shows heavy fuel consumption of >7 kg dry matter 326 (DM) m⁻² in the Taiga Plain and in the Western and Eastern Mixed Wood Shield, where 327 boreal spruce fuel types (C2) dominate. 328

329 We rely on the DC index from the CFWIS in order to assign the moisture condition 330 and determine the monthly fuel consumption. This index is a good indicator for fuel moisture content (Bourgeau-Chavez et al., 1999; Abbott et al., 2007) and has been widely 331 332 used to calculate fuel consumption (e.g., de Groot et al., 2009; Kasischke and Hoy, 2012). 333 Higher DC values indicate greater dryness. Figure S1 shows the monthly mean DC in 334 boreal ecoregions for 1980-2009. The values of DC increase gradually from May to 335 September, as fuels become progressively drier. The DC values in western ecoregions are 336 usually higher than those in eastern ones, probably because precipitation in the West 337 (except for the Pacific coast) is much lower relative to that in the East (not shown).

Figure S2 shows the cumulative probability of daily DC in all ecoregions during the fire seasons of 1980-2009. This probability distribution differs somewhat from the distributions in Amiro et al. (2004) who estimated DC for Canadian wildfires larger than 2 km² in different ecosystems during 1959-1999. Such fires typically occur in June to August. In contrast, Figure S2 shows the DC distribution over the entire fire season,

343 including days in September and October, when DC values are usually very high. We 344 relate burning severity to DC by defining four arbitrary thresholds in the DC probability 345 distribution: 85%, 65%, 35%, and 15%. The resulting moisture categories and their 346 average DC indices are as follows: extra dry (DC>85%, 774), dry (65%<DC≤85%, 590), moderately dry (35%<DC≤65%, 390), moist (15%<DC≤35%, 196), and wet (DC≤15%, 347 348 53). We then calculate the monthly fuel consumption in each ecoregion by matching the 349 DC in that month to these moisture categories and choosing the appropriate fuel 350 consumption (Table S2). In this way, fuel consumption varies yearly and seasonally. 351 Amiro et al. (2004) found that the average DC for Canadian wildfires ranges from 210 to 352 372 depending on the ecoregion, and the cumulative probability of the DC also varies 353 with ecoregion. Here we have chosen to use a single distribution for the North American boreal region to define the DC thresholds (Figure S2). As a check, we also compare the 354 fuel consumption derived in this way with that calculated based on the ecoregion-specific 355 356 DC thresholds (see Table 4 and related discussion in Section 3.3).

We assume that the fuel load remains constant for both present day and midcentury, 357 based on the conclusion that changes in forest composition will be a gradual process 358 359 (Hanson and Weltzin, 2000). Fuel consumption per unit area burned, however, does change in our approach since it depends on the moisture state. We estimate fuel 360 consumption for both present day and midcentury based on the multi-model median DC 361 in each ecoregion. As a result, the modeled fuel consumption responds to trends in fuel 362 363 moisture conditions. Amiro et al. (2009) performed a similar estimate of future boreal 364 fuel consumption using modeled monthly mean values of the DC and an empirical relationship derived by de Groot et al. (2009) for forest floor fuel consumption in 365 experimental fires in Canada. However, this empirical relationship has predictive 366 capability only for fires set under experimental conditions, but not for wildfires (de Groot 367 et al., 2009), and we do not apply it here. 368

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371 2.7 Estimate of gridded fire emissions

372 We calculate biomass burned as the product of area burned and fuel consumption. 373 The annual area burned estimated with regressions for each ecoregion (Section 2.4) is 374 first converted to monthly area burned using the mean seasonality for each boreal 375 ecoregion, on the basis of the observations for 1980-2009. Large fires tend to burn in 376 ecosystems with a history of similarly large fires (Keane et al., 2008). Fuel availability, 377 however, limits reburning in the same location during the forest return interval, which is 378 typically ~200 years for Canadian forests (Ter-Mikaelian et al., 2009; de Groot et al., 379 2013). We assume a random distribution of area burned within each ecosystem, to allow for these tendencies. 380

We spatially allocate monthly area burned within each ecoregion to $1^{\circ} \times 1^{\circ}$ as follows. 381 In each 1°×1° grid square we calculate the frequency of fires larger than 1000 ha during 382 383 1980-2009; such fires account for ~85% of total area burned in Canada and Alaska over 384 this time period. Accordingly, we arbitrarily attribute 85% of area burned within each ecoregion to fires of 1000 ha in size, and we then allocate these large fires among the 385 $1^{\circ} \times 1^{\circ}$ grid squares based on the observed spatial probability of large fires (>1000 ha), 386 387 which is the percentage of total large fires of the ecoregion located in a specific grid box 388 during this timeframe. We then disaggregate the remaining 15% of area burned into fires 389 10 ha in size, and randomly distribute these fires across all grid boxes in the ecoregion. 390 We apply this random approach to calculate both present day (1997-2001) and future 391 (2047-2051) biomass burned. Within each timeframe, the effect of limited fuel availability in the aftermath of a fire is taken into account by reevaluating the spatial 392 probability distribution of area burned at each monthly time step. We scale the observed 393 394 probabilities by the fraction remaining unburned in each grid box, and then use this 395 modified probability distribution to allocate large fires for the remaining months. Using sensitivity tests, we find that specifying different areas burned to the large fires (100 ha or 396 10000 ha rather than 1000 ha) yields <1% changes in predicted biomass burned, 397

suggesting that this approach is not sensitive to the presumed fire size in the allocation procedure.

400 We take the emission factors for all ozone precursors except nitric oxide (NO) from Andreae and Merlet (2001). For NO we average the values from six studies of forest fires 401 in the western U.S. (Table S3), yielding 2.2 g NO_x kg DM^{-1} . Based on the measurements 402 403 by Hegg et al. (1990), which showed that NO contributes 30% of fire-induced NO_x, this value is equivalent to 1.6 g NO kg DM⁻¹, consistent with the mean emission ratio of 1.4 g 404 NO kg DM⁻¹ derived from measurements from Alaskan fires (Nance et al., 1993; Goode 405 406 et al., 2000). Our NO emission factor is ~50% higher than that derived by Alvarado et al. (2010) from aircraft measurements of boreal fire plumes. They also found that 40% of 407 NO_x emissions are rapidly converted to peroxyacetyl nitrate (PAN) in fresh plumes. We 408 use the emission factor of 1.6 g NO kg DM⁻¹ and neglect the rapid formation of PAN for 409 410 our simulations, recognizing that this likely leads to a small overestimate of ozone 411 formation immediately downwind of the fires. The emission factors from Andreae and Merlet (2001) have recently been updated by Akagi et al. (2011) and Urbanski (2014). As 412 413 a check, we compare the predicted fire emissions using all three sets of emission factors 414 (see Table S6 and related discussion in Section 3.3).

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416 2.8 GEOS-Chem CTM and simulations

417 We simulate tropospheric ozone-NOx-VOC-aerosol chemistry using the GEOS-Chem 418 global 3-D model of tropospheric chemistry version 8.03.01, driven by present-day and 419 future simulated meteorological fields from the NASA/GISS Model 3 with 4°×5° resolution (Wu et al., 2007; Wu et al., 2008b). Compared with finer resolution, 4°×5° 420 421 resolution does not induce a significant bias in surface ozone and captures the major 422 synoptic features over the United States (Fiore et al., 2002; Fiore et al., 2003), though it may underestimate the average ozone level by 1-4 ppbv and predict fewer pollution 423 episodes (Wang et al., 2009; Zhang et al., 2011). The simulated daily and monthly ozone 424

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429	concentrations from the GEOS-Chem model driven with meteorological reanalyses have
430	been widely validated with site-level, aircraft, and satellite observations (Fiore et al.,
431	2002; Wang et al., 2009; Alvarado et al., 2010; Zhang et al., 2011). Monthly mean ozone
432	concentrations simulated with GISS meteorology have been evaluated by comparison
433	with climatological ozonesonde data and reproduces values throughout the troposphere
434	usually to within 10 ppbv (Wu et al., 2007). In addition, simulated daily ozone with GISS
435	meteorology reasonably reproduces the summertime temporal variability of ozone
436	concentrations as well as the pollution episodes in U.S. (Wu et al., 2008b).
437	Anthropogenic emissions for ozone precursors, including NO _x , CO, and non-methane
438	VOCs are as described in Table 1 a of Wu et al. (2008b), and are summarized here for
439	completeness and transparency. Global emissions of NO_x and CO are upscaled from the
440	1°×1° Emissions Database for Global Atmospheric Research (EDGAR) version 3
441	(Olivier and Berdowski, 2001). Anthropogenic VOC emissions are derived from the
442	Global Emission Inventory Activity (GEIA) (Benkovitz et al., 1996). Over the North
443	American domain, these global emissions are replaced with the EPA National Emissions
444	Inventory (NEI) 2005 inventory (http://www.epa.gov/). All the anthropogenic emissions
445	are kept constant at the level of the year 2000 for both present day and future simulations,
446	to isolate the effects of changes in biomass burning emissions. However, natural
447	emissions of these gases from vegetation, soil, and lightning are computed locally based
448	on the meteorological variables within the model and allowed to change with climate.
449	Emissions of biogenic hydrocarbons are calculated with the Model of Emissions of Gases
450	and Aerosols from Nature (MEGAN), version 2.1 (Guenther et al., 2012). The lightning
451	source of NOx is computed locally in deep convection events using the scheme of Price
452	and Rind (1992), which relates number of flashes to convective cloud top heights,
453	together with the vertical NO_x distribution from Pickering et al. (1998).
454	Stratosphere-troposphere exchange (STE) is specified by the Synoz flux boundary
455	condition (McLinden et al., 2000) with a prescribed global annual mean flux of 495 Tg

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	ozone by up to 10 ppbv
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	winds in GISS GCM relative to observations
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465 ozone $\sqrt{r^{-1}}$ for both present day and future simulations. Outside of North America, we use 466 climatological biomass burning emissions derived from the inventory described in Lobert 467 et al. (1999), with seasonality from Duncan et al. (2003) and placed into the boundary 468 layer.

Over North America, we apply the biomass burning emissions predicted by our 469 method. For the western U.S., we use area burned predicted with regressions from Yue et 470 al. (2013). We update the fire emissions over southern California with our improved fire 471 scheme (Yue et al., 2014). For Canada and Alaska, we use the fire emissions derived 472 473 from calculated area burned and the estimated fuel consumption. We do not change the emissions over the eastern U.S., which are dominated by prescribed agricultural fires (Liu, 474 2004). The GEOS-Chem model is not coupled with a plume model, and as a result cannot 475 simulate the impacts of plume rise. As in Leung et al. (2007), we emit 20% of emissions 476 in each grid square to the model levels between 3 and 5 km and leave the rest in the 477 478 boundary layer, as observations have shown that over 80% of plumes from North America fires are located in the boundary layer (Val Martin et al., 2010). In calculating 479 480 photolysis rates within the plume, the model takes into account the attenuation of solar 481 radiation by fire aerosols. This calculation has some importance; in their model study, 482 Jiang et al. (2012) found that fire aerosols alone could reduce ozone concentrations by up 483 to 15% close to the source due to the light extinction.

Surface ozone concentrations in the 21st century will be influenced not just by trends 484 485 in wildfire emissions, but also by changes in atmospheric transport, temperature, 486 cloudiness, wet and dry deposition, and natural/anthropogenic emissions. To isolate the changes due to biomass burning emissions, we conduct an ensemble of 5-year 487 simulations for present day (1997-2001) and the mid-21st century (2047-2051) for a total 488 489 of 9 sensitivity studies (Table 1). Two simulations, FULL PD and NOFIRE PD, are carried out with present-day climate: FULL PD considers present-day fire emissions 490 from both western U.S. and boreal forests, while NOFIRE PD omits any fire emissions 491

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494	in these regions. Five simulations are conducted with future climate. In FULL_A1B, we
495	additionally implement the projected future fire emissions from western U.S. and boreal
496	forests, while NOFIRE_A1B omits these emissions. Simulation WUS_FIRE applies
497	future fire emissions in western U.S. but the present-day emissions in boreal forests. In
498	contrast, BOREAL_FIRE uses present-day emissions in western U.S. but the future ones
499	for boreal regions. The last simulation with future climate, CLIM_CHAN, applies
500	present-day fire emissions everywhere as in FULL_PD. Finally, we perform another two
501	sets of simulations, one for present day (FULL_PD_EF) and the other for midcentury
502	(FULL_A1B_EF), both of which use emission factors from Akagi et al. (2011), to
503	estimate the modeling uncertainties due to emission factors.
504	We examine the differences between FULL_PD and NOFIRE_PD to quantify the
505	impacts of wildfire emissions in the present day, and the differences between FULL_A1B
506	and NOFIRE_A1B to quantify these impacts at midcentury. We use the differences
507	between FULL_A1B and BOREAL_FIRE to isolate the impacts of increased fire
508	emissions in western U.S. at midcentury. The differences between FULL_A1B and
509	WUS_FIRE reveal the effects due to changes of fire emissions in boreal forests, also at
510	midcentury. The differences between CLIM_CHAN and FULL_PD represent the impacts
511	due solely to climate change on the simulated ozone concentrations. We calculate the
512	differences between FULL_PD_EF and FULL_PD to quantify the present-day
513	uncertainties due to the emission factors, and the differences between FULL_A1B_EF
514	and FULL_A1B to quantify these uncertainties at midcentury. Each model run was
515	initialized with a 1-year spin-up. Taken together, these 7 cases yield insight into the
516	influence of changing wildfire activity on surface ozone concentrations across North
517	America, and the relative importance of local versus remote wildfires on U.S. and
518	Canadian ozone air quality,
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520	3 Results

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523 3.1 Regressions and predictions of area burned at present day

524 Figure 3a shows observed, annual mean area burned for 1980-2009 averaged over the 525 boreal ecoregions. In Canada, the Western Mixed Wood Shield exhibits the greatest area burned of nearly 7×10^5 ha yr^{-1} . In addition, large area burned of $\sim 4 \times 10^5$ ha yr^{-1} and 526 $\sim 3 \times 10^5$ ha vr^{-1} is observed in the Taiga Plain and the Western Taiga Shield. Most fires in 527 528 these very remote ecoregions are allowed to burn naturally, without intervention. This 529 practice, together with the hot summers typical of continental interiors, leads to large area 530 burned (Stocks et al., 2002). The Western Cordillera shows the least area burned, at 0.4×10^5 ha yr⁻¹, due to abundant rainfall as well as active fire suppression (Stocks et al., 531 532 2002). Fires in Alaska are about three times larger in the Alaska Boreal Interior than in the Alaska Boreal Cordillera, because the summer in interior Alaska is warmer and drier 533 relative to the southern part, which is influenced by moisture from the Pacific (Wendler et 534 al., 2011). In each ecoregion, the top three largest fire years account for 36-67% the total 535 536 area burned in 1980-2009, with the largest fraction in the Alaska Boreal Cordillera 537 (Figure 4).

Table 2 shows the regressions we developed between area burned and the suite of 538 539 meteorological variables and fire weather indices in each ecoregion. These fits explain 34-75% (p < 0.001) of the variance in area burned (Figure 3b). In most ecoregions, the 540 regressions capture well the interannual variations of area burned, although they usually 541 542 underestimate the values for extreme years (Figure 4). For the top three large fire years in 543 each ecoregion, the predictions underestimate the total area burned by 22-57%, with the 544 worst match in the Hudson Plain. Such failure in predicting extreme fires is a common 545 weakness of fire models, no matter the approach - e.g., regressions (Balshi et al., 2009; Spracklen et al., 2009; Yue et al., 2013), parameterizations (Crevoisier et al., 2007; 546 547 Westerling et al., 2011), and dynamic global vegetation models (DGVMs; Bachelet et al., 2005). The leave-one-out cross validation shows RMSE/SD ratios between 0.53-1.1 in 548 boreal ecoregions (Table 4), suggesting that the prediction error is usually smaller than 549

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the variability of data. In a comparable study, Littell et al. (2009) calculated
cross-validated RMSE/SD ratios of 0.56-2.08 for area burned in western U.S. ecoregions
during 1977-2003. Our prediction shows much lower RMSE/SD ratios, indicating that the
derived regressions (Table 4) are reasonably robust for the future projections.

558 We find that meteorological variables for the current year are selected as the first term 559 in ten of the twelve ecoregions, indicating that area burned in the boreal forests is most 560 related to current weather (Table 2). In contrast, Westerling et al. (2003) suggested that 561 wildfire activity in shrub ecoregions in the western U.S. is closely related to meteorology 562 in previous years, because the antecedent moisture levels can control fuel growth. In boreal forests, however, fuel load is perennially abundant, and so weather in the current 563 year is more important here. Our regressions show that the 500 hPa height is the 564 dominant factor affecting boreal fires, as it appears in eight regression fits and is selected 565 as the first term for three of them. Temperature, which highly correlates with geopotential 566 567 height (R>0.85) in spring and summer, is selected as the first term in three other ecoregions. Of the six ecoregions that have either geopotential height or temperature as 568 the first term, five are located in Alaska and western Canada, suggesting that wildfire 569 570 activity in these areas is greatly influenced by temperature or by blocking highs that lead 571 to persistent hot and dry conditions. Since our regression method does not permit 572 correlation among the predictors, temperature and geopotential height are not selected for 573 the same season and year in any of the ecoregions. Fire indices, which combine the 574 impacts from temperature, humidity, and wind speed, are the dominant predictors in the 575 four central Canadian ecoregions. In three of these four regions, moisture variables such as relative humidity and precipitation are also selected. Our method yields relative 576 577 humidity as the leading term in the two eastern ecoregions, indicating that the dryness of fuel is most important for wildfire activity there. 578

579 Our results confirm that wildfires in Alaska and western Canada are related to 580 geopotential height anomalies, which are associated with the positive phase of either the

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583 Pacific North American (PNA) pattern or the Pacific Decadal Oscillation (PDO; Fauria

and Johnson, 2006, 2008). <u>However, in some of the central and eastern Canadian</u> ecoregions (e.g. Taiga Plain and Eastern Taiga Shield), such height anomalies are not selected as terms in our regressions (Table 2). Although geopotential height may still influence wildfire activity in those areas, this variable tends to correlate with fire weather indices or moisture variables. We attempt to avoid collinearity in our regressions, and so geopotential height may not be selected as a predictor there.

590 We compared our results with those in Flannigan et al. (2005), who developed 591 regressions in similar ecoregions. Relative to their R^2 of 0.56 and 0.60 in the Taiga Plain and the Western Mixed Wood Shield, where large area burned is observed (Figure 3a), 592 our regressions yield higher R^2 of 0.75 and 0.67. This improvement may result from our 593 use of meteorological data with better spatial coverage or our inclusion of terms 594 dependent on the meteorology in previous years. However, our regressions in the 595 596 Western Taiga Shield, the Eastern Taiga Shield, and the Hudson Plain explain 34-46% of the variance in observed area burned, much lower than the 64% predicted in Flannigan et 597 al. (2005), which aggregated these three ecoregions into one. The larger domain in 598 599 Flannigan et al. (2005) apparently smoothed spikes in the area burned data (Figure 4) and as a result increased the R^2 for regressions (Spracklen et al., 2009). We treat the three 600 regions separately due to their very different ecologies. 601

602 We next calculate present-day (1983-1999) area burned by applying present-day 603 meteorological fields from the 13 GCMs to our regressions. We start with 1983 since we 604 need to apply factors from the previous two years in the regressions. As Figure 5a shows, in eight ecoregions the median area burned from the ensemble of GCMs matches the 605 606 observations within $\pm 15\%$. However, the predicted area burned is overestimated by 54% in the Eastern Taiga Shield and underestimated by 30% In the Taiga Plain. These biases 607 do not derive from the long-term mean model meteorology, since we scale the simulated 608 fields with means from observations. Instead, the biases arise from our use of fire weather 609

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Xu Yue 8/19/15 12:09 PM Formatted 616 indices in the regressions, which depend on the daily variability in meteorology. For 617 example, in the Taiga Plain, the predicted median ISI is lower than observed by 7%. In 618 the same ecoregion, the site records show that more than 30% of days have precipitation less than 0.1 mm day⁻¹ during fire seasons for 1980-2009. However, the GCMs predict 619 only 2-13% days with < 0.1 mm day⁻¹, even after scaling with the means from 620 621 observations. In contrast, they predict 55-65% of days with rainfall of 0.1-1.0 mm day⁻¹, 622 much more than the 37% from observations. The overprediction of drizzle, a common 623 problem in GCMs (Mearns et al., 1995), results in lower ISI compared with observations. The same problem in modeled precipitation also reduces the predicted DMC_{max} in the 624 Eastern Taiga Shield, leading to an overestimate in area burned when applied with a 625 negative coefficient. Flannigan et al. (2005) reported a similar problem in their study, and 626 they subtracted a constant from the GCM precipitation to match the observed rainfall 627 frequency. We do not follow this approach because our predicted present-day median 628 629 area burned agrees reasonably well with that observed. The non-linear response of fire weather indices to daily meteorology contributes to the uncertainty of predictions, 630 resulting in larger spread of ratios for those ecoregions whose regressions depend on the 631 632 fire indices (Table 2).

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3.2 Projection of area burned at midcentury 634

635 Figure 6 shows the changes in key meteorological variables at midcentury relative to 636 present day, as predicted by the 13 GCMs. Temperatures across all ecoregions show 637 median increases of ~2°C during the fire season, with all models predicting significant changes. Meanwhile, precipitation rates increase by 0.05-0.23 mm day⁻¹ in the median, 638 likely as a result of a poleward shift of mid-latitude storm tracks and precipitation (Yin, 639 2005). However, these increases in precipitation are significant for only 4 to 8 GCMs, 640 depending on the ecoregion, and in some ecoregions some models project a drier climate 641 by midcentury, reflecting the large uncertainty in model projections of regional 642

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hydrology (Christensen et al., 2007). The 500-hPa geopotential heights are predicted to
rise by 2050, with median increases of 30-60 m (0.6-1%) and these changes are
significant for all GCMs.

649 We find that the wildfire response to these trends in meteorological variables varies 650 greatly by ecoregion, with large increases in area burned by 2050 in Alaska and western 651 Canada, but little or no change in area burned elsewhere (Figure 5b). The median area 652 burned at midcentury increases by 130-350% in Alaska and the western Canadian ecoregions, relative to present day (Figures 5b, 7a and Table 3). The greatest increase in 653 area burned occurs in the Alaska Boreal Cordillera, where area burned at the midcentury 654 is more than four times that of the present day. These increases in Alaska and western 655 Canada are largely driven by changes in temperature and/or geopotential height (Table 656 S4), and as a result are statistically robust in 11 to 13 GCMs, depending on the ecoregion 657 (Figure 7b). The central and southern Canadian ecoregions show more moderate and less 658 robust increases in area burned of 40-90%, with only 3-8 models projecting significant 659 660 changes. In these ecoregions, fire activity depends either on hydrological variables (e.g., RH for the Eastern Mixed Wood Shield) or on fire indices that combine effects from 661 temperature and moisture (e.g., the fire indices DSR and FWI in the Boreal Plain and the 662 fire index BUI in the Western Mixed Wood Shield; Table 2). As a result, the effects of 663 increased precipitation in these ecoregions may partly offset the effects of rising 664 temperatures on wildfires. 665

In some of the most northern ecoregions within the Canadian interior, median area burned decreases in the wetter climate of the midcentury. In the Taiga Plain, the median area burned decreases by 50% (Table 3, Figure 7a) despite the 1.7°C increase in temperature (Figure 6a). In the Western Taiga Shield, where area burned is projected as a function of the fire index ISI (positive relationship, Table 2) and relative humidity, the median area burned shows a small, insignificant decrease in the future atmosphere (Table 3, Figure 7b), because the increases of rainfall significantly reduce ISI there. In the

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Eastern Taiga Shield, where area burned is a function of the fire index DMC (negative
relationship, Table 2) and relative humidity, the median area burned again shows an
insignificant decrease by mid-century (Table 3, Figure 7b). DMC is related to both
temperature and precipitation. Here rising temperatures enhances DMC and outweighs
the effects of greater humidity (Table S4).

687 Our projection of larger increases in Alaska and western Canadian ecoregions are consistent with the observed trends for 1959-1999 in Kasischke and Turetsky (2006) and 688 with the projection by Flannigan et al. (2005) for 2080 to 2100. However, Flannigan et al. 689 690 (2005) predicted area burned increases of 40-60% in the Taiga Plain with 3×CO₂, where we project a decrease of 50% with $\sim 1.5 \times CO_2$. The reasons for this discrepancy are not 691 clear. In our results, a median increase of 0.1 mm day^{-1} in summer precipitation drives the 692 decrease in area burned in the Taiga Plain, but Flannigan et al. (2005) did not report their 693 trend in modeled precipitation. In addition, our regression for the Taiga Plain has ISI as 694 695 the leading term, while the leading term in Flannigan et al. (2005) is temperature. Based on the same GCM meteorology as Flannigan et al. (2005) and using a similar approach, 696 Amiro et al. (2009) found a modest increase of 10% in area burned with 2×CO₂ for the 697 698 Taiga Plain, the lowest enhancement among all Canadian ecoregions for that study.

699

700 **3.3 Estimate of future fire emissions**

701 We first compare our derived fuel consumption with previous studies. Figure 8a 702 shows the mean annual biomass burned for 1980-2009, calculated from monthly areas 703 burned and monthly fuel consumption (Section 2.6). Figure 2b shows the mean fuel consumption per unit area during the fire season for 1980-2009. We find that the mean 704 705 fuel consumption per unit area is $\sim 30\%$ less than that for moderately dry conditions for 706 which we assumed an average DC of 390 (Figure 2). Most boreal area burned occurs during the relatively moist months of June and July (Figure S1), when the monthly 707 average DC is usually less than 370 (Amiro et al., 2004). In the eastern ecoregions 708

(Hudson Plain, Eastern Taiga Shield, and Eastern Mixed Wood Shield), the values for
mean fuel consumption are as much as 50% less than those for moderately dry conditions
due to high moisture content in fuel there (Figure S1).

In Table 4 we compare our estimates for mean fuel consumption with those from 712 713 other studies, which were derived from forest inventories and field measurements (French 714 et al., 2000; Balshi et al., 2007), fuel-weather models (Amiro et al., 2001; Amiro et al., 715 2009), and biogeochemical models based on satellite observations (van der Werf et al., 716 2010). We also compare our results with estimates based on wildfire incidents (Table S5). In the Alaska Boreal Interior, our estimate of 5.5 kg DM m⁻² is within $\sim 10\%$ of those by 717 718 Balshi et al. (2007) and van der Werf et al. (2010), but is $\sim 25\%$ lower than that of French 719 et al. (2000). Turetsky et al. (2011) collected data from 178 sites in the Alaskan black spruce ecosystem and estimated that average fuel consumption is 5.9 kg DM m^{-2} for early 720 season fires (May-July) but increases to 12.3 kg DM m⁻² for late season fires (after July 721 31; Table S5). Based on our compilation of fuel consumption (Table 2) and the calculated 722 monthly DC values for Alaska (Figure S1), we find similar results of 6.1 kg DM m⁻² for 723 May-July and 14.6 kg DM m⁻² for August-October for C2 fuel (boreal spruce). A recent 724 725 analysis by French et al. (2011) showed that different models of fuel consumption provide very different results for a given fire, with a range of 2.7-12.2 kg DM m⁻² for a 726 727 major fire in Alaska in 2004 (Table S5). The CONSUME model (v. 3.0) yielded 2.8-4.7 kg DM m⁻² for moderate to very dry conditions for that fire, while a field study estimated 728 5.2 kg DM m^{-2} (French et al., 2011). 729

There is less consistency among different estimates of mean fuel consumption in the Canadian ecoregions (Table 4). Our estimates fall in the range of previous work for most ecoregions except for the Western Cordillera and the Taiga Plain, where our values are ~100% higher than most other estimates. These two ecoregions are located in the western Canada, where seasonal DC is usually high, indicating relatively dry conditions (Figure S1). Our moisture categories derived from the single DC probability distribution (Figure

S2) may overestimate fuel dryness in the west. On the other hand, our estimates show low 736 737 fuel consumption in the eastern ecoregions, such as Eastern Taiga Shield, Hudson Plain, 738 and Eastern Mixed Wood Shield, consistent with most of other studies. In a sensitivity test, we derive fuel consumption with regional DC thresholds based on ecoregion-specific 739 740 probability distributions. This approach reduces western fuel consumption by 8-16%, but 741 increases eastern values by 2-37% (Table 4). It also predicts lower Alaskan fuel consumption compared with other studies. The boreal biomass burned calculated with 742 this alternative approach is about 156.2 Tg DM yr⁻¹ for 1980-2009, almost identical to 743 744 that estimated using a single probability distribution to define the DC thresholds (Figure 8a). 745

We estimate fuel consumption at present day and midcentury with the median DC 746 values from the multi-model ensemble. The present-day values are close to the ones 747 based on observed meteorology (Table 4). By the midcentury, DC values increase in the 748 749 warming climate, indicating drying, and fuel consumption increases by 2-22%, depending on the ecoregion, with a 9% average enhancement. Using the random method described 750 in section 2.7, we derive gridded area burned based on the projection with regressions. 751 752 The estimated biomass burned, averaged over 1997-2001 (Figure 8b) correlates with observations averaged over 1980-2009 (Figure 8a) with $R^2 = 0.5$ for ~1700 boreal grid 753 squares, indicating that our prediction captures the observed spatial pattern reasonably 754 well. The total biomass burned of 160.2 Tg DM yr⁻¹ is just 2.5% higher than that obtained 755 756 with the observed area burned. 757 Estimates of fire emissions depend on the emission factors. Using the same biomass

burned calculated with observed area burned, we calculate three different sets of
emissions using the factors from Andreae and Merlet (2001) (except for NO, see Table
S3), Akagi et al. (2011), and Urbanski (2014) (Table S6). These emissions show similar
magnitudes in CO and NH₃, but some differences in NO_x and non-methane organic
compounds (NMOC). For example, NO_x from Akagi et al. (2011) is higher by 30-50%

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768	than that in Urbanski (2014) and in Table S3. Meanwhile, NMOC from Andreae and
769	Merlet (2001) is lower by 20% than that in Akagi et al. (2011) and Urbanski (2014). In
770	the following simulations and analyses, we use emission factors from Andreae and Merlet
771	(2001) (except for NO from Table S3) and discuss the modeling uncertainties due to the
772	application of different emission factors.
773	Our value of biomass burned using the regression yields emissions of 0.27 Tg yr^{-1} for
774	NO and 18.6 Tg yr ⁻¹ for CO in Alaska and Canada at the present day. By the midcentury,
775	we find that total biomass burned across the boreal ecoregions increases by ~90% (Figure
776	8c) due to the \sim 70% increase in area burned and the \sim 10% increase in average fuel
777	consumption (Table 4). In Alaska, the maximum increase of 36 Tg DM yr ⁻¹ (168%) is
778	predicted for the Alaska Boreal Interior, where area burned by the 2050s increases by 146%
779	(Table 3). In Canada, the Western Mixed Wood Shield has the highest increase of 29 Tg
780	DM $\sqrt{r^{-1}}$ (64%). These changes in biomass burned result in increases of 0.24 Tg $\sqrt{r^{-1}}$ for
781	NO emissions and 17.1 Tg vr^{-1} for CO in boreal regions. Over the western U.S., the ~80%
782	enhancement in biomass burned yields an increase in NO emissions, from 0.03 Tg yr^{-1} in
783	the present day to 0.05 Tg yr^{-1} in the future climate, and an increase in CO emissions
784	from 1.9 to 3.4 Tg <u>vr</u> ⁻¹ .
785	
786	3.4 Impacts of wildfire on ozone air quality
787	Daily maximum 8-hour average (MDA8) surface ozone is a metric used by the U.S.
788	Environmental Protection Agency (EPA) to diagnose ozone air quality. In this study, we

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American in summer (June-July-August, JJA).
MDA8

use MDA8 ozone instead of daily mean ozone for all the analyses and discussion. Figure

9a shows the simulated MDA8 surface ozone, averaged over North American in summer

(June-July-August, JJA). We focus on the summer season, when fire activity peaks in

both the U.S. and Canada. The figure shows mean MDA8 values of 40-75 ppbv across

the U.S., with the maximum in the East due to the local anthropogenic emissions (Fiore et

al., 2002). The concentrations in Alaska and Canada range from 20 to 60 ppbv. However,

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for most regions north of 55°N, MDA8 is generally less than 40 ppbv. As shown in Figure 9b, we find that wildfire emissions in these far northern areas contribute 1-10 ppbv to average JJA surface ozone concentrations, with a mean contribution of 4 ppbv. These values are considerably larger than the average 1 ppbv contribution of wildfires to surface ozone that we calculate in the western U.S. (Figure 9b) because of the much higher biomass burning emission in Alaska. In the eastern U.S., wildfires make almost no contribution to mean surface ozone in summer.

815 The increased fire emissions that we calculate at midcentury result in greater ozone 816 pollution across North America (Figure 9c). We find a maximum JJA mean perturbation 817 of 22 ppby along the border between Alaska and Canada, where the largest increase in future area burned is projected (Figure 7a). In central Canada, the future fire emissions 818 contribute 6-9 ppbv to JJA mean ozone concentrations. For the western U.S., the fire 819 perturbation for surface ozone is about 2 ppby, with the largest values of 3-5 ppby in the 820 821 Pacific Northwest and Rocky Mountain Forest ecoregions. Relative to the present-day 822 contribution, the fire perturbation at the midcentury enhances JJA mean surface ozone by 823 an additional <u>4.6 ppbv in Alaska</u>, 2.8 ppbv in Canada, and 0.7 ppbv in the western U.S. 824 (Figure 9d), indicating a degradation in air quality. Our estimate of future fire impacts 825 depends on the emission factors we adopted. Using emission factors from Akagi et al. (2011), we calculate larger fire-induced ozone enhancements at both present day and 826 827 midcentury (Figure S3). As a result, simulations with emission factors from Akagi et al. 828 (2011) project ozone increases of 5.5 ppbv in Alaska, 3.2 ppbv in Canada, and 0.9 ppbv 829 in the western U.S. by future wildfire emissions. These enhancements are 14-23% higher 830 than our previous estimates with emission factors from Andreae and Merlet (2001) and 831 Table S3.

A key question is to what extent boreal fires affect the more populated regions of lower latitudes. In Figure 10, we investigate the contributions of climate, local and boreal wildfire emissions, and atmospheric transport to JJA mean surface ozone concentrations

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In Figure 11 we examine the impact of wildfire emissions on the frequency of ozone 852 pollution episodes. In the northwestern U.S., where the impact of fire emission is 853 especially large (Figure 10c), surface ozone above the 95th percentile (i.e., on the 5 most 854 polluted days in summer) increases by 2 ppbv at the midcentury (Figure 11a). 855 856 Simulations without fire emissions show an increase of 1 ppbv above the same percentile, 857 indicating that the increased wildfire emission alone contributes a 1 ppbv enhancement during ozone pollution episodes in this region. The changes are more significant for 858 Alaska and Canada, where we predict large increases in fire activity (Figure 9c). As 859 Figure 11b shows, climate change alone decreases ozone above the 95th percentile ozone 860 by an average ~3 ppbv in Alaska, likely because of the effects of enhanced water vapor 861 862 on background ozone (Wu et al., 2008a). However, when changes in fire emissions are included, the simulation predicts that ozone above the 95th percentile instead increases by 863 12 ppbv at midcentury, suggesting a positive change of 15 ppbv due to wildfire alone. 864 Over high latitudes in Canada, climate change decreases the 95th percentile ozone by 1 865 ppby; however, the inclusion of future fire perturbation enhances it by 4 ppby (Figure 866 11c), indicating that the contribution from wildfire may be as great as 5 ppbv. 867

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869 4 Discussion and conclusions

870 We examined the effects of changing wildfire activity in a future climate on 871 June-August MDA8 ozone over the Western U.S., Canada, and Alaska by the midcentury. 872 We built stepwise regressions between area burned and meteorological variables in 12 873 boreal ecoregions. These regressions explained 34-75% of the variance in area burned for 874 all ecoregions, with 500 hPa geopotential heights and temperatures the driving factors. 875 With these regressions and future meteorology from an ensemble of climate models, we 876 predicted that the median area burned increases by 150-390% in Alaska and the western 877 Canadian ecoregions by the midcentury due to enhanced 500 hPa geopotential heights and temperatures. The area burned shows moderate increases of 40-90% in the central 878 and southern Canadian ecoregions, but a 50% decrease in the Taiga Plain, where most of 879 the GCMs predict increases in precipitation at midcentury. Using the GEOS-Chem CTM, 880 881 we found that fire perturbation at the midcentury enhances summer mean daily maximum 8-hour surface ozone by 5 ppbv in Alaska, 3 ppbv in Canada, and 1 ppbv in the western 882 U.S. The changes in wildfire emissions have larger impacts on pollution episodes, as 883 884 ozone above the 95th percentile increases by 15 ppbv in Alaska, 5 ppbv in Canada, and 1 885 ppbv in northwestern U.S.

Our study represents the first time that multi-model meteorology has been used to 886 887 project future area burned in Alaskan and Canadian forest. The individual models in our 888 study predict changes in area burned of different magnitudes or even of opposite sign, but 889 the median values and the spread in model results provide an estimate of both the sign and the uncertainty of these projections. We find the projections are most robust over 890 Alaska and western Canada, where for almost all GCMs we calculate significant 891 892 increases in area burned (Figure 7b; Table 3). For these regions, wildfire activity is largely associated with blocking highs and the resulting hot, dry weather, and both 893 temperature and geopotential height show consistent and significant increases here in all 894

climate models (Figure 6). However, for northern Canada, where the control of blocking systems on area burned is weaker, we projected a less robust decreasing trend in area burned, due to the competing effects of hotter weather and wetter conditions. The multi-model ensemble approach allows us to identify the most robust changes in the future wildfire activity due to climate change, and as a result should be more reliable than predictions using only 1-2 models, which can yield very different projections especially for northern Canada (e.g., Wotton et al., 2010).

Our approach neglects the impacts of topography, human activity, and fuel changes on wildfire trends. The aggregation method used here for each ecoregion may hide the spatial variation of both area burned and meteorological variables and obscure their relationships (Balshi et al., 2009; Meyn et al., 2010). Changes in fire domain and climate may lead to changes in forest composition (DeSantis et al., 2011), resulting in different fire severity and spread efficiency (Thompson and Spies, 2009).

908 For our study, we assumed that fuel load remains constant for 50 years, but we calculated a 9% average increase in fuel consumption in boreal regions. Our assumption 909 910 of constant fuel load is justified at least for the conterminous U.S. since trends in 911 heavy-fuel load in U.S. forests are likely to be gradual (Hanson and Weltzin, 2000). For 912 boreal regions, recent simulations with DGVMs show that large-scale forest die back may 913 occur in coming decades, due to intense heat and drought (Heyder et al., 2011). In 914 addition, mountain pine beetle outbreaks are important disturbances for both boreal and 915 U.S. forests, leading to changes in fuel load and fuel moisture with climatic shifts (Fauria and Johnson, 2009; Simard et al., 2011; Jenkins et al., 2014). We did not consider these 916 917 effects in this study.

Compared with previous studies, our estimate of fuel consumption shows higher
values over western Canada (Table 4), where the largest increase in future area burned is
predicted (Figure 7a), suggesting that the boreal fire emissions might be overestimated.
However, our estimate of a 9% increase in fuel consumption may, in fact, be conservative.

Some DGVM studies predict 30-40% increases in burning severity for U.S. Pacific Northwest forest by the end of the 21st century (Rogers et al., 2011). Moreover, observations have suggested that large area burned sometimes results in burning at greater soil depth than is typical (Turetsky et al., 2011). Thus the projected increase in fire areas may amplify future fuel consumption, leading to even larger emissions than predicted in this study.

928 The emission from boreal wildfires in our simulation shows limited contributions to 929 ozone concentrations in downwind areas, but causes significant local ozone enhancement 930 in Alaska and Canada. However, observations point to uncertainties in the relationship 931 between wildfire activity and ozone. First, the emission factors of ozone precursors are 932 not well constrained, especially for NO_x. Sensitivity tests with emission factors from Akagi et al. (2011) show 14-23% higher fire-induced ozone than that with emission 933 factors from Andreae and Merlet (2001) and the NO_x emission factor derived from an 934 935 ensemble of experiments (Table S3). Using aircraft data from boreal fires, Alvarado et al. (2010) determined an emission factor of 1.1 g NO kg DM⁻¹, lower than our value of 1.6 g 936 NO kg DM⁻¹ and much lower than the estimate of 3.0 g NO kg DM⁻¹ for extratropical 937 938 forest fires in Andreae and Merlet (2001). Alvarado et al. (2010) found that 40% of 939 wildfire NO_x is rapidly converted to PAN and 20% to HNO₃ and his estimate of 1.1 g NO 940 kg DM⁻¹ for fresh emissions includes these two species. Second, observations do not 941 consistently reveal ozone enhancements during wildfire events. Jaffe et al. (2008) found a 942 significant correlation between interannual variations of observed surface ozone and area 943 burned in the western U.S. Using the same ozone dataset, however, Zhang et al. (2014) did not find regional ozone enhancements during wildfire events, when such 944 945 enhancements would be expected to be large. In their review, Jaffe and Wigder (2012) reported that increased ozone is observed in most plumes, but with huge variability in the 946 enhancement ratio of $\Delta O_3 / \Delta CO$ within the plume. Alvarado et al. (2010), on the other 947 hand, found that only 4 out of 22 plumes showed enhanced ozone. Such discrepancies in 948

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952 plume data may be attributed to differences in plume age (Alvarado et al., 2010), 953 emissions of wildfire NO_x and VOCs (Zhang et al., 2014), or plume photochemistry 954 (Verma et al., 2009; Jiang et al., 2012). Third, the effect of long-range transport of 955 wildfire PAN on ozone downwind is not well known. Observations suggest that PAN 956 forms rapidly in fresh fire plumes and may enhance ozone downwind as it decomposes 957 (Real et al., 2007; Jaffe and Wigder, 2012). In their model study, Fischer et al. (2014) 958 reported a large effect of fires on PAN in the high northern latitudes but limited impacts 959 over the downwind areas in U.S. In any event, our use of a moderately high NOx 960 emission factor and omission of rapid PAN formation within the plume may lead to an overestimate of fire-induced ozone in local areas (Alvarado et al., 2010). 961 Uncertainties may also originate from limitations in the model configuration. First, 962 GEOS-Chem CTM does not allow feedbacks of fire emissions to affect model 963 meteorology or biogenic emissions. Second, we estimated fire-induced O₃ concentrations 964 using monthly emissions, due to the limits in the temporal resolution of predicted area 965 burned. Such an approach may have moderate impacts on the simulated O₃; Marlier et al. 966 967 (2014) found ≤ 1 ppb differences in surface [O₃] over North America between simulations 968 using daily and monthly fire emissions. The same study also predicted <10% differences in the accumulated exceedances for MDA8 O3 globally. Third, the projections were 969 970 performed at coarse spatial resolution of 4°×5°. As shown in Zhang et al. (2011), 971 however, mean MDA8 O₃ in a nested grid simulation (0.5°×0.667°) is only 1-2 ppbv 972 higher than that at 2°×2.5° resolution in the GEOS-Chem model. Fiore et al. (2002) 973 reached a similar conclusion in comparing simulations at 4°×5° and 2°×2.5°. They found that the coarse model resolution smoothed the regional maximum, resulting in a more 974 975 conservative estimate of the intensity of pollution episodes. 976 Given these limitations, our estimate with a multi-model ensemble consistently shows

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that wildfire activity will likely increase in North American boreal forest by the
midcentury, especially in western Canada and Alaska. Our study suggests that area

989 burned could increase by 130-350% in these two regions, while in central and southern 990 Canada, where most people reside, area burned could increase 40-90%. In north central 991 Canada, the competition between increased temperature and precipitation in the future 992 atmosphere results in uncertainty in the projections for area burned. Overall, these trends 993 in boreal wildfire activity may amplify the threat of wildfires to Canadian residents, 994 increase the expense of fire suppression, and lead to more ozone pollution both locally 995 and in the central and western U.S. The regional perturbation of summer ozone by future 996 wildfires can be as high as 20 ppbv over boreal forests, suggesting large damage to the 997 health and carbon assimilation of the ecosystems (Pacifico et al., 2015). Using a newly developed model of ozone vegetation damage (Yue and Unger, 2014), we plan to explore 998 the response of boreal ecosystems to fire-induced ozone enhancements. 999

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1001 Acknowledgments

1002 We thank Nancy H. F. French for her helpful suggestions on calculating boreal fuel consumption with the CONSUME-python model. We thank Emily V. Fischer for her 1003 1004 help in codifying fire emissions above the boundary layer in the GEOS-Chem CTM. We 1005 acknowledge the Program for Climate Model Diagnosis and Intercomparison (PCMDI) 1006 and the WCRP's Working Group on Coupled Modeling (WGCM) for their roles in 1007 making available the WCRP CMIP3 multi-model dataset. Support of this dataset is 1008 provided by the Office of Science, U.S. Department of Energy. This work was funded 1009 by STAR Research Assistance agreement R834282 awarded by the U.S. Environmental 1010 Protection Agency (EPA). Although the research described in this article has been funded 1011 wholly or in part by the EPA, it has not been subjected to the Agency's required peer and 1012 policy review and therefore does not necessarily reflect the views of the Agency and no 1013 official endorsement should be inferred. Research reported in this publication was supported in part by the NASA Air Quality Applied Science Team and the National 1014 1015 Institutes of Health (NIH) under Award Numbers 1R21ES021427 and 5R21ES020194.

- 1016 The content is solely the responsibility of the authors and does not necessarily represent
- 1017 the official views of the NIH.

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Table 1. Summary of simulations in this study. 1422

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	Simulations	Western U.S. fire emissions	Boreal fire emissions	Climate	Emission factors	Xu Yue 8/19/15 12:09 PM Inserted Cells
	FULL_PD	present-day ^a	present-day	present-day	<u>AM2001 ^c</u>	Formatted Table
	FULL_A1B	future ^b	future	future	<u>AM2001</u>	
	NOFIRE_PD	none	none	present-day	<u>AM2001</u>	
	NOFIRE_A1B	none	none	future	<u>AM2001</u>	
	WUS_FIRE	future	present-day	future	<u>AM2001</u>	
	BOREAL_FIRE	present-day	future	future	<u>AM2001</u>	
	CLIM_CHAN	present-day	present-day	future	<u>AM2001</u>	
	FULL_PD_EF	present-day	present-day	present-day	A2011	Yu Vuo 8/10/15 12:00 DM
	FULL A1B FF	future	future	future	A2011	Deleted: CLIM_CHAN
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- ^a Present-day denotes 1997-2001. 1425
- ^b Future denotes 2047-2051. 1426

 $^{\rm c}$ Emission factors from Andreae and Merlet (2001) and $\rm NO_x$ emission factor from an 1427

- ensemble of experiments (Table S3). 1428
- ^d Emission factors from Akagi et al. (2011) 1429
- 1430
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1434 **Table 2.** Regression fits ^a for each aggregated ecoregion.

Ecoregion	Regressions ^a	\mathbb{R}^2	RMS
Alaska Boreal Interior	$2.2 \times 10^5 \text{ T}_{\text{max}}.\text{SUM} + 5.7 \times 10^3 \text{ HGT}.\text{SUM(-1)} - 8.1 \times 10^4 \text{ ISI}_{\text{max}}(-1) - 3.5 \times 10^7$	60%	<u>/SD</u> <u>0.66</u>
Alaska Boreal Cordillera	5.8×10^{3} HGT.SUM + 4.8×10^{4} T _{max} .AUT(-2) + 4.6×10^{4} T.SPR - 3.3×10^{7}	61%	<u>0.87</u>
Taiga Cordillera	$5.7 \times 10^4 T_{max}$.ANN(-2) + $2.8 \times 10^3 HGT$.SUM - 1.5×10^7	36%	<u>0.98</u>
Canadian Boreal Cordillera	7.6×10^3 HGT.SUM – 4.2×10^7	52%	<u>0.82</u>
Western Cordillera	$3.5 \times 10^4 T_{max}.SUM - 8.3 \times 10^2 HGT.SPR + 6.4 \times 10^2 DMC_{max}(-1) + 3.7 \times 10^6$	53%	<u>0.85</u>
Taiga Plain	9.8×10^5 ISI - 5.9×10^5 Prec.FS(-1) - 1.5×10^6	75%	<u>0.53</u>
Boreal Plain	Prec. Win -4.7×10^{6} 8.8×10 ⁴ DSR _{max} + 5.1×10 ⁴ RH.SUM(-2) + 2.1×10 ⁴ FWI _{max} (-1) - 4.0×10 ⁶	52%	<u>0.86</u>
Western Taiga Shield	$1.9 \times 10^5 ISI_{max} + 5.7 \times 10^4 RH.AUT - 6.0 \times 10^6$	46%	<u>1.03</u>
Eastern Taiga Shield	5.4×10^4 RH.WIN(-2) - 6.2×10^4 RH.ANN - 7.7×10^3 DMC _{max} (-2) + 1.2×10^6	38%	<u>1.10</u>
Hudson Plain	2.4×10^{3} HGT.SUM - 1.8×10^{4} T.SPR - 1.6×10^{4} T = WIN(1) - 1.4×10^{7}	34%	<u>1.03</u>
Western Mixed Wood Shield	1_{max} . W IN(-1) = 1.4×10 2.0×10 ⁴ BUI _{max} + 8.3×10 ³ HGT.SUM - 4.7×10 ⁷	67%	<u>0.55</u>
Eastern Mixed Wood Shield	-6.7×10^4 RH.SUM + 2.8×10 ³ HGT.AUT(-1) - 1.0×10 ⁷	43%	<u>0.81</u>

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1436	^a The values (-1) or (-2) after a predictor indicate that the meteorological field is one or
1437	two years earlier than current area burned. Variables are T (temperature), T _{max} (maximum
1438	temperature), RH (relative humidity), Prec (precipitation), HGT (geopotential height),
1439	and fire indexes from CFWIS, such as Duff Moisture Code (DMC), Build-up Index
1440	(BUI), Initial Spread Index (ISI), and Daily Severity Rating (DSR). Meteorological fields
1441	are averaged for winter (WIN, DJF), spring (SPR, MAY), summer (SUM, JJA), autumn
1442	(AUT, SON), fire season (FS, MJJASO), and the whole year (ANN). The order of the
1443	terms indicates their contributions to the R^2 in the regression.
1444	^b Ratios between predicted residual sum of squares (PRESS) root mean square error

1445 (RMSE) and standard deviation (SD) as an indicator of the leave-one-out prediction error.

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Ecoregions	Observed ^a (1983-1999)	Present Day Regression ^b (1983-1999)	Future Regression ^b (2048-2064)	Ratio ^c (Future/ Present)	# of models ^d (p<0.05)	# of models ^e (M±30%)
Alaska Boreal Interior	2.1 ± 3	3.7 ± 2.9	9.7 ± 3.6	2.46	12	6
Alaska Boreal Cordillera	0.6 ± 1	1.1 ± 1.3	5.3 ± 1.7	4.85	13	10
Taiga Cordillera	0.9 ± 1.7	0.9 ± 0.8	3.3 ± 0.7	3.26	13	11
Canadian Boreal Cordillera	1.3 ± 1.3	1.7 ± 1.3	4.5 ± 1.4	2.64	13	13
Western Cordillera	0.2 ± 0.2	0.3 ± 0.4	0.8 ± 0.4	2.66	11	11
Taiga Plain	3.8 ± 4.6	2.5 ± 2.7	1.6 ± 1.9	0.48	5	5
Boreal Plain	2.4 ± 3.5	2.6 ± 2.7	4.7 ± 3.2	1.44	3	8
Western Taiga Shield	3.7 ± 7.1	4 ± 4.3	4.1 ± 3.7	0.96	0	9
Eastern Taiga Shield	1.9 ± 4.3	2 ± 1.2	1.6 ± 1.2	0.86	1	11
Hudson Plain	1 ± 1.6	0.9 ± 0.5	1 ± 0.5	1.2	2	9
Western Mixed Wood Shield	6.8 ± 7.4	7.3 ± 4.8	11.1 ± 5.1	1.65	8	9
Eastern Mixed Wood Shield	1.7 ± 1.8	1.8 ± 1.3	3.3 ± 1.6	1.91	8	8

1448 Table 3. Observed and projected area burned in boreal ecoregions.

^a AB = area burned (10⁵ ha yr⁻¹). Results in each ecoregion are shown as $\overline{AB} \pm \sigma$. \overline{AB} is 1449 the long-term average of the AB during fire season (May-October), and σ is the standard 1450 1451 deviation.

^b Results in each ecoregion are the median values of \overline{AB} and σ predicted using the 1452 meteorological fields from 13 GCMs for the A1B scenario. 1453

^c Results in each ecoregion represent the median value of the 13 ratios of future AB to 1454 present-day AB, calculated with the GCM meteorology. 1455

^d Number out of 13 models that predict a significant (p<0.05) increase in AB in each 1456

ecoregion, as determined by the Student t-test. 1457

^e Number out of 13 models that predict a ratio within $\pm 30\%$ of the median ratio. 1458

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1461 **Table 4.** Fuel consumption ^a in boreal ecoregions, as reported by recent studies.

Ecoregions	French et	Amiro et	Amiro et al. (2009) ^d	Balshi et al. (2007) ^e	GFED3 ^f	This study ^g		
Leoregions	al. (2000) ^b	al. (2001) ^c				1980-2009	PD	A1B
Alaska Boreal Interior	7.5	N/A	N/A	4.9	5.2	5.5 (4.6)	5.4	5.6
Taiga Cordillera	N/A	3.1	N/A	N/A	2.7	3.8 (3.5)	3.6	3.7
Can. Boreal Cordillera	5.4	3.2	N/A	7.2	3.5	5.5 (4.7)	5.2	6.0
Western Cordillera	N/A	3.9	N/A	N/A	2.7	6.6 (5.9)	6.2	7.0
Taiga Plain	2.9	2.9	3.5	3.3	5.4	7.2 (6.6)	7.7	8.2
Boreal Plain	3.8	2.4	2.8	6.8	2.1	5.6 (5.0)	5.7	5.8
W. Taiga Shield	1.0	1.9	1.5	1.8	5.3	3.9 (3.9)	4.9	5.4
E. Taiga Shield	1.6	1.9	1.7	3.0	4.0	1.8 (2.2)	2.3	2.8
Hudson Plain	1.7	1.9	N/A	2.9	6.7	3.1 (4.1)	3.3	3.8
W. Mixed Wood Shield	2.1	2.5	3.0	5.7	4.9	6.4 (6.6)	6.4	6.9
E. Mixed Wood Shield	2.6	2.0	2.4	0.5	2.9	3.0 (4.1)	3.1	3.6

^a Fuel consumption unit is kg DM m⁻² burned. For some studies that use units of kg C m⁻²

1464 burned, we multiply their values by 2 g DM g^{-1} C. DM denotes dry matter.

^b Values are averages of 1980-1994.

^c Values are averages of 1959-1995.

¹⁴⁶⁷ ^d Values are estimated for forest floor fuel consumption in a GCM 1×CO₂ scenario.

^e Values are averages of 1959-2002, estimated with the same burning severity parameters

1469 as French et al. (2000) but with modeled vegetation and soil carbon pool.

¹⁴⁷⁰ ^f GFED3: Global Fire Emission Database version 3 for 1997-2010.

1471 g Results are the fuel consumption weighted by area burned and drought code (DC) for

1472 1980-2009, using the DC thresholds determined by a single probability distribution for

1473 North America. As a comparison, the values calculated with ecoregion-specific DC

1474 thresholds are shown in brackets. For PD and A1B, values are calculated using predicted

1475 median DC for present day (1996-2001) and midcentury (2046-2051) from the

1476 multi-model projection.

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1462

1478 Figure Captions

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Figure 1. Distribution of the 12 ecoregions used for this study. The black triangle
symbols indicate the GSOD meteorological data sites in Alaskan and Canadian
ecoregions.

1483

Figure 2. Fuel consumption over Alaska and Canada (a) for moderately dry conditions
and (b) weighted by the Drought Code (DC) and area burned for 1980-2009. The average
values are shown in brackets.

1487

1488 Figure 3. (a) Observed annual area burned and (b) fraction of the variance in observed area burned explained by the regression in each ecoregion for the period of 1980-2009 1489 (R²). The ecoregions are: Alaska Boreal Interior (ABI), Alaska Boreal Cordillera (ABC), 1490 Taiga Cordillera (TC), Canadian Boreal Cordillera (CBC), Western Cordillera (WC), 1491 1492 Taiga Plain (TP), Boreal Plain (BP), Western Taiga Shield (WTS), Eastern Taiga Shield (ETS), Hudson Plain (HP), Western Mixed Wood Shield (WS), and Eastern Mixed Wood 1493 1494 Shield (ES). Observations are compiled using fire reports from the Fire and Aviation 1495 Management Web Applications (FAMWEB) for Alaska and those from the Canadian 1496 National Fire Database (CNFD) for Canada.

1497

Figure 4. Observed (red solid lines) and predicted (blue dashed lines) area burned (10^5 ha) for 1980-2009 in boreal ecoregions. The area burned is calculated using the regressions for the fire season (May-October) for each ecoregion. Site-based<u>meteorological</u> observations from GSOD are used in the prediction. The fraction of the variance in observed area burned explained by the regression (R²) is shown on each panel.

1503

Figure 5. (a) Ratios of modeled to observed area burned for 1983-1999 and (b) the ratios
 of midcentury (2048-2064) to the present-day (1983-1999) area burned, as projected by 50

1506 an ensemble of GCMs. The ecoregions are: Alaska Boreal Interior (ABI), Alaska Boreal

1507 Cordillera (ABC), Taiga Cordillera (TC), Canadian Boreal Cordillera (CBC), Western

1508 Cordillera (WC), Taiga Plain (TP), Boreal Plain (BP), Western Taiga Shield (WTS),

1509 Eastern Taiga Shield (ETS), Hudson Plain (HP), Western Mixed Wood Shield (WS), and

1510 Eastern Mixed Wood Shield (ES). Different symbols are used for each model. The black

bold lines indicate the median ratios. Note the difference in scale between the two panels.

Figure 6. Calculated changes in (a) surface air temperature, (b) precipitation, and (c) 1513 1514 geopotential height at 500 hPa during the fire season (May-October) in 2048-2064 relative to 1983-1999. Results are from an ensemble of GCMs for the A1B scenario. The 1515 ecoregions are: Alaska Boreal Interior (ABI), Alaska Boreal Cordillera (ABC), Taiga 1516 Cordillera (TC), Canadian Boreal Cordillera (CBC), Western Cordillera (WC), Taiga 1517 1518 Plain (TP), Boreal Plain (BP), Western Taiga Shield (WTS), Eastern Taiga Shield (ETS), Hudson Plain (HP), Western Mixed Wood Shield (WS), and Eastern Mixed Wood Shield 1519 1520 (ES). Different symbols are used for each model. The black bold lines indicate the 1521 median changes.

1522

1523 Figure 7. (a) Median ratios of midcentury (2048-2064) to present day (1983-1999) area 1524 burned in each boreal ecoregions, as predicted by an ensemble of GCMs and (b) the 1525 number of GCMs out of 13 total which predict significant changes of the same sign as the median. The ecoregions are: Alaska Boreal Interior (ABI), Alaska Boreal Cordillera 1526 1527 (ABC), Taiga Cordillera (TC), Canadian Boreal Cordillera (CBC), Western Cordillera (WC), Taiga Plain (TP), Boreal Plain (BP), Western Taiga Shield (WTS), Eastern Taiga 1528 1529 Shield (ETS), Hudson Plain (HP), Western Mixed Wood Shield (WS), and Eastern Mixed 1530 Wood Shield (ES).

- 1532 Figure 8. Biomass burning (BB) in Alaska and Canada in terms of dry matter (DM)
- 1533 burned per year, calculated as the product of area burned and fuel consumption. Panel (a)
 - 51

shows values based on observations for 1980-2009, (b) the predicted values for 1535 1996-2001, and (c) the projections for 2046-2051. The differences between midcentury 1536 and present day (c-b) are shown in (d). Annual mean values summed over the whole 1537 domain are shown in brackets. Units: Tg DM \sqrt{r}^{-1} .

1538

Figure 9. (a) Simulated present-day MDA8 ozone at the surface in summer (June-August). Panel (b) shows the contribution to MDA8 summertime ozone by wildfire emissions in the present day (FULL_PD – NOFIRE_PD), and Panel (c) shows the same contribution, but at midcentury (FULL_A1B – NOFIRE_A1B). Panel (d) presents the change in the contribution of wildfires to MDA8 ozone between the two periods (i.e., c – b). Descriptions of the sensitivity simulations are given in Table 1. The color scale saturates at both ends.

1546

Figure 10. (a) Simulated changes in MDA8 ozone at the surface in summer (June-August) at the midcentury relative to the present day (FULL_A1B – FULL_PD) over the western and central United States. The other three panels show the contributions to the changes in Panel (a) from (b) climate change (CLIM_CHAN – FULL_PD), (c) changes in fire emissions in the western U.S. (FULL_A1B – BOREAL_FIRE) and (d) changes in fire emissions in Alaska and Canada (FULL_A1B – WUS_FIRE). Descriptions of the sensitivity simulations are given in Table 1.

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Figure 11. Simulated cumulative probability distributions of MDA8 ozone at the surface in summer (June-August) over (a) northwestern U.S. (>40°N), (b) Alaska, and (c) Canada (>55°N) for different scenarios. Black shows the present-day (1997-2001) climate without wildfire emissions; green shows future (2047-2051) climate without wildfire emissions; blue indicates present-day climate including the associated wildfire emissions; and red indicates future climate including the associated wildfire emissions. Each point

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- 1562 represents the value in one grid square within each region for each day during the five
- 1563 model summers (1997-2001 or 2047-2051).

Boreal Ecoregions Image: Descent of the second of

Figure 1. Distribution of the 12 ecoregions used for this study. The triangles indicate the GSOD meteorological data sites in Alaska and Canada.

(a) Fuel consumption for moderately dry conditions (4.7)



(b) Fuel consumption weighted by DC and area burned (3.4)



Figure 2. Fuel consumption over Alaska and Canada (a) for moderately dry conditions and (b) weighted by the Drought Code (DC) and area burned for 1980-2009. The average values are shown in brackets.


Figure 3. (a) Observed annual area burned and (b) fraction of the variance in observed area burned explained by the regression in each ecoregion for the period of 1980-2009 (R²). The ecoregions are: Alaska Boreal Interior (ABI), Alaska Boreal Cordillera (ABC), Taiga Cordillera (TC), Canadian Boreal Cordillera (CBC), Western Cordillera (WC), Taiga Plain (TP), Boreal Plain (BP), Western Taiga Shield (WTS), Eastern Taiga Shield (ETS), Hudson Plain (HP), Western Mixed Wood Shield (WS), and Eastern Mixed Wood Shield (ES). Observations are compiled using fire reports from the Fire and Aviation Management Web Applications (FAMWEB) for Alaska and those from the Canadian National Fire Database (CNFD) for Canada.



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Figure 5. (a) Ratios of modeled to observed area burned for 1983-1999 and (b) the ratios of midcentury (2048-2064) to the present-day (1983-1999) area burned, as projected by an ensemble of GCMs. The ecoregions are: Alaska Boreal Interior (ABI), Alaska Boreal Cordillera (ABC), Taiga Cordillera (TC), Canadian Boreal Cordillera (CBC), Western Cordillera (WC), Taiga Plain (TP), Boreal Plain (BP), Western Taiga Shield (WTS), Eastern Taiga Shield (ETS), Hudson Plain (HP), Western Mixed Wood Shield (WS), and Eastern Mixed Wood Shield (ES). Different symbols are used for each model. The black bold lines indicate the median ratios. Note the difference in scale between the two panels.



Figure 6. Calculated changes in (a) surface air temperature, (b) precipitation, and (c) geopotential height at 500 hPa during the fire season (May-October) in 2048-2064 relative to 1983-1999. Results are from an ensemble of GCMs for the A1B scenario. The ecoregions are: Alaska Boreal Interior (ABI), Alaska Boreal Cordillera (ABC), Taiga Cordillera (TC), Canadian Boreal Cordillera (CBC), Western Cordillera (WC), Taiga Plain (TP), Boreal Plain (BP), Western Taiga Shield (WTS), Eastern Taiga Shield (ETS), Hudson Plain (HP), Western Mixed Wood Shield (WS), and Eastern Mixed Wood Shield (ES). Different symbols are used for each model. The black bold lines indicate the median changes.



Figure 7. (a) Median ratios of midcentury (2048-2064) to present day (1983-1999) area burned in each boreal ecoregions, as predicted by an ensemble of GCMs and (b) the number of GCMs out of 13 total which predict significant changes of the same sign as the median. The ecoregions are: Alaska Boreal Interior (ABI), Alaska Boreal Cordillera (ABC), Taiga Cordillera (TC), Canadian Boreal Cordillera (CBC), Western Cordillera (WC), Taiga Plain (TP), Boreal Plain (BP), Western Taiga Shield (WTS), Eastern Taiga Shield (ETS), Hudson Plain (HP), Western Mixed Wood Shield (WS), and Eastern Mixed Wood Shield (ES).



Figure 8. Biomass burning (BB) in Alaska and Canada in terms of dry matter (DM) burned per year, calculated as the product of area burned and fuel consumption. Panel (a) shows values based on observations for 1980-2009, (b) the predicted values for 1996-2001, and (c) the projections for 2046-2051. The differences between midcentury and present day (c-b) are shown in (d). Annual mean values summed over the whole domain are shown in brackets. Units: Tg DM yr⁻¹.



Figure 9. (a) Simulated present-day MDA8 ozone at the surface in summer (June-August). Panel (b) shows the contribution to MDA8 summertime ozone by wildfire emissions in the present day (FULL_PD – NOFIRE_PD), and Panel (c) shows the same contribution, but at midcentury (FULL_A1B – NOFIRE_A1B). Panel (d) presents the change in the contribution of wildfires to MDA8 ozone between the two periods (i.e., c – b). Descriptions of the sensitivity simulations are given in Table 1. The color scale saturates at both ends.



Figure 10. (a) Simulated changes in MDA8 ozone at the surface in summer (June-August) at the midcentury relative to the present day (FULL_A1B – FULL_PD) over the western and central United States. The other three panels show the contributions to the changes in Panel (a) from (b) climate change (CLIM_CHAN – FULL_PD), (c) changes in fire emissions in the western U.S. (FULL_A1B – BOREAL_FIRE) and (d) changes in fire emissions in Alaska and Canada (FULL_A1B – WUS_FIRE). Descriptions of the sensitivity simulations are given in Table 1.



Figure 11. Simulated cumulative probability distributions of MDA8 ozone at the surface in summer (June-August) over (a) northwestern U.S. (>40°N), (b) Alaska, and (c) Canada (>55°N) for different scenarios. Black shows the present-day (1997-2001) climate without wildfire emissions; green shows future (2047-2051) climate without wildfire emissions; blue indicates present-day climate including the associated wildfire emissions; and red indicates future climate including the associated wildfire emissions. Each point represents the value in one grid square within each region for each day during the five model summers (1997-2001 or 2047-2051).