Detecting the effect of climate change on Canadian forest fires

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[1] The area burned by forest fires in Canada has increased over the past four decades, at the same time as summer season temperatures have warmed. Here we use output from a coupled climate model to demonstrate that human emissions of greenhouse gases and sulfate aerosol have made a detectable contribution to this warming. We further show that human-induced climate change has had a detectable influence on the area burned by forest fire in Canada over recent decades. This increase in area burned is likely to have important implications for terrestrial emissions of carbon dioxide and for forest ecosystems. INDEX TERMS: 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1610 Global Change: Atmosphere (0315, 0325); 1620 Global Change: Climate dynamics (3309); 1630 Global Change: Impact phenomena; 9350 Information Related to Geographic Region: North America. Citation: Gillett, N. P., A. J. Weaver, F. W. Zwiers, and M. D. Flannigan (2004), Detecting the effect of climate change on Canadian forest fires, Geophys. Res. Lett., 31, L18211, doi:10.1029/2004GL020876.

1. Introduction

[2] Last year, forest fires in British Columbia made the news worldwide, when they destroyed over two hundred homes, and forced the evacuation of thirty thousand people [Armstrong, 2003]. Although 2003 was not a record fire year over Canada as a whole, the area burned by wildland fires in Canada each year has shown a pronounced upward trend over recent decades [Van Wagner, 1988; Skinner et al., 1999, 2002; Podur et al., 2002; Stocks et al., 2003], consistent with predictions that the area burned in Canada will double by the end of the century [Flannigan et al., 2004] and the length of the fire season will increase [Wotton and Flannigan, 1993; Stocks et al., 1998]. At the same time, several recent studies have demonstrated that human emissions of greenhouse gases and sulfate aerosol have had a detectable warming effect on North American climate [Zwiers and Zhang, 2003; Karoly et al., 2003; Stott, 2003]. Here we show first that human emissions of greenhouse gases and sulfate aerosol have had a detectable warming effect during the fire season in the fire-prone regions of Canada, and second, applying a statistical model to simulated temperature changes, we demonstrate that human-induced climate change has had a significant effect on the area burned by forest fires in Canada.

2. Results

[3] The geographical distribution of fires was evaluated by summing the area burned by fires greater than 200 ha in size [Stocks et al., 2003] over Canada on a $5° \times 5°$ grid for the period 1959–1999 (Figure 1). Although these large fires represent only 3.1% of the total number of fires, they represent ~97% of the area burned. The largest areas burned are found in West-Central and Northwest Canada in the boreal forest and taiga, due to their continental climates and low rates of fire suppression [Stocks et al., 2003]. Lightning is the most important source of ignition, accounting for ~85% of the total area burned [Stocks et al., 2003]. A second database of total area burned in Canada from 1920–1999, with corrections applied to account for regions with missing data [Van Wagner, 1988], was used to evaluate the temporal evolution of wildland fire in Canada. The anomaly in total area burned in each five year period is shown by the black line in Figure 2. Five year totals were used because annual area burned varies by as much as an order of magnitude from year to year, and in this analysis we wish to concentrate on lower frequency changes. As has been noted by other authors, the area burned by wildland fires has increased since the 1960s [Van Wagner, 1988; Skinner et al., 1999, 2002; Podur et al., 2002; Stocks et al., 2003]. Although an attempt was made to account for fires in provinces and territories with incomplete records [Van Wagner, 1988], prior to the advent of satellite monitoring in the early 1970s some fires may be missing from the record due to lack of observations or incomplete record-keeping [Stocks et al., 2003]. However, the fact that the largest increase in area burned has occurred since 1970 indicates that it is unlikely that the upward trend is purely an artifact of under-reporting, as do studies of area burned restricted to well-observed regions [Podur et al., 2002]. The upward trend has occurred despite an increase in areas under fire suppression and more efficient fire suppression techniques, including the use of water bombers [Van Wagner, 1988]. While there is debate on the effects of fire suppression over large areas and longer timescales [Miyanishi and Johnson, 2001; Ward et al., 2001], in the absence of climate influence, we might have anticipated a decrease in area burned with time.
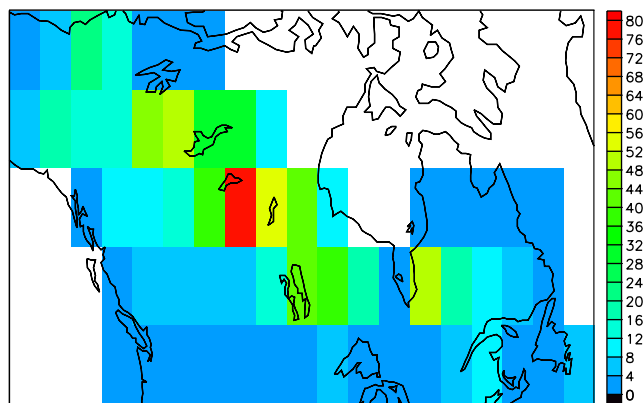
Figure 1. Total area burned over Canada in each $5° \times 5°$ grid cell from 1959 to 1999 from the Large Fire Database [*Stocks et al.*, 2003], in 1000 km^2.

[4] Although forest fires are influenced by a range of climate parameters, such as temperature, humidity, precipitation, wind speed and lightning occurrence, in long term means, temperature is perhaps the best predictor of area burned [*Flannigan and Harrington*, 1988]. By contrast, monthly mean precipitation and wind speed are only weakly correlated with area burned in each province [*Flannigan and Harrington*, 1988]. Temperature is also better observed than other climate variables. In this analysis we therefore use monthly mean observations of temperature on a $5° \times 5°$ grid from 1920 to 1999 [*Jones and Moberg*, 2003], and take 5-year means over the principal fire season of May−August [*Stocks et al.*, 2003]. In order to give greatest weight to temperature anomalies in fire-prone regions, the temperature in each $5° \times 5°$ grid cell is then weighted by the total area burned in that grid cell over the 1959–1999 period (Figure 1), and a mean is computed over available data, shown by the red line in Figure 2. Since the weights used are fixed in time no artificial temporal correlation between temperature and area burned is introduced. Consistent with an observed warming trend in Canadian summer temperatures in individual station data [*Zhang et al.*, 2000], this weighted mean also shows a pronounced warming over recent decades. As is suggested by inspection of Figure 2, this mean temperature is also highly correlated with total area burned in Canada ($r = 0.77$), explaining 59% of the variance of the five year totals (if both series are first detrended, $r = 0.61$, and temperature explains 37% of the variance): thus temperature is indeed a good predictor of area burned. What then has caused the warming trend in Canada over recent decades?

[5] We compare observed temperature anomalies with temperatures simulated by the second Canadian Climate Centre for Modelling and Analysis model (CGCM2) [*Flato et al.*, 2000; *Flato and Boer*, 2001]. Five year May−August mean temperature anomalies from an ensemble of three integrations forced with historical greenhouse gas and sulfate aerosol changes [*Flato and Boer*, 2001] were interpolated onto the observational $5° \times 5°$ grid, sampled where observations exist, weighted by total area burned in each grid cell (Figure 1), and averaged. The resulting ensemble-mean anomalies are shown by a green line in Figure 2. Simulated Canadian summer temperatures show a warming

since the 1960s similar to that observed, suggesting that the recent warming trend may be anthropogenic. In order to robustly attribute observed changes to anthropogenic affects, we might also consider the simulated response to natural forcings, such as volcanic aerosol and changes in solar irradiance. Unfortunately no such simulations have been carried out with CGCM2, but *Karoly et al.* [2003] show that natural forcing has made no significant contribution to North American temperature trends over the 20th century, thus we expect the effect of natural forcings on our analysis to be small. In order to obtain a quantitative measure of the consistency between simulated and observed temperature changes, and to assess whether or not the observed changes could be due to internal variability, we next applied an optimal detection analysis.

[6] Our optimal detection approach assumes that the observed five-year mean temperature anomalies ($\mathbf{T_{o5}}$) may be represented as the linear sum of the scaled model-simulated response to greenhouse gases and sulfate aerosol ($\mathbf{T_{m5}}$), itself containing a component due to internal variability ($\mathbf{v}$), and internal variability in the observations ($\mathbf{u}$):

$$\mathbf{T_{o5}} = \beta_T(\mathbf{T_{m5}} - \mathbf{v}) + \mathbf{u} \qquad (1)$$

We estimate β_T using a total least squares regression to take account of the effect of internal climate variability on the simulated response, $\mathbf{T_{m5}}$, as well as its effect on $\mathbf{T_{o5}}$ [*Allen and Stott*, 2003]. Internal variability was estimated from a 1009-year control integration of CGCM2. We project data onto the first 10 temporal Empirical Orthogonal Functions (EOFs) of control variability, and apply a signal to noise
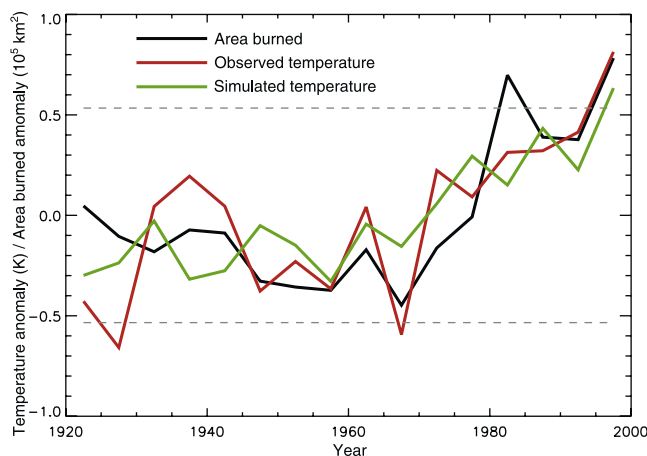

Figure 2. The black line shows total area burned anomalies over Canada for each five year period from 1920 to 1999 [*Van Wagner*, 1988], in units of 10^5 km^2. The red line shows five year mean observed May−August temperature anomalies [*Jones and Moberg*, 2003] weighted by area burned, in K. The green line shows ensemble-mean five-year-mean May−August area-burned-weighted temperature anomalies from integrations of the CGCM2 model forced with anthropogenic greenhouse gases and sulfate aerosol. Gray dashed lines indicate the 5−95% range of internal variability in area burned, estimated from inter-annual variability. All anomalies are calculated relative to the 1920−1999 mean.
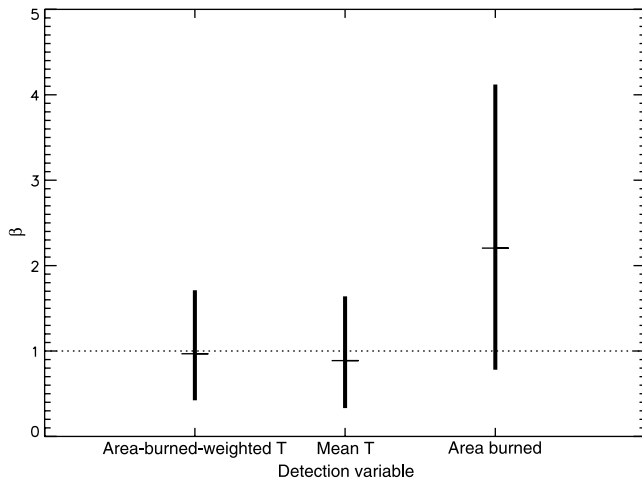
Figure 3. Regression coefficients, β, of observed changes in temperature and area burned over Canada, against changes simulated in response to greenhouse gas and sulfate aerosol increases. The first bar shows results derived using five year mean 1920–1999 May–August temperature anomalies [*Jones and Moberg*, 2003] weighted by the area burned in each grid cell over Canada, and the second bar shows results derived using a simple area-weighted mean temperature over all the grid cells experiencing forest fire. The third bar shows the results of a regression of observed changes in five year total area burned against simulated changes in area burned. The bars show 5–95% uncertainty ranges.

optimisation. We check that this model provides a good fit to the observed data by testing whether the residual, **u**, is consistent with control variability at the 5% level [*Allen and Tett*, 1999]. The uncertainty in β_T is then assessed from control variability and an anthropogenic response is detected if β_T is found to be significantly greater than zero.

[7] The value of β_T for the area-burned-weighted May–August temperature (as shown in Figure 2) was found to be inconsistent with zero (Figure 3), indicating that there is a detectable anthropogenic signal in Canadian fire season temperatures. The regression coefficient is also consistent with one, and the residuals are consistent with control variability, indicating that the simulated response to greenhouse gas and sulfate aerosol changes provides a good fit to the observed temperature variations. Similar results were obtained for an area-weighted mean over all grid cells experiencing fires during the 1959–1999 period (Figure 3), indicating that the results are not sensitive to the weighting used. All the detection results presented in this paper were also found to be robust to reductions in the period analyzed to 35 years (1964–1999). These results therefore demonstrate a clear anthropogenic influence on this important climate driver of forest fire.

[8] *Skinner et al.* [1999] argue that changes in forest fires are strongly linked to variations in 500-hPa height, and *Skinner et al.* [2002] show that positive local anomalies in geopotential height are associated with increased area burned. Using May–August NCEP reanalysis 500-hPa geopotential height over the period 1950–1999, we found a detectable anthropogenic influence over Canada, consistent with increasing trends in geopotential height in observations

and model. However, on a global scale a residual test [*Allen and Tett*, 1999] indicated that simulated geopotential height changes did not provide a good fit to observed changes. Thus, since both the temperature and geopotential height trends reflect a warming of the lower troposphere, and since temperature is better observed and more reliably simulated, we concentrate further analysis on temperature. Is there also a detectable signal of anthropogenic climate change in forest fire data themselves?

[9] In order to test whether observed changes in area burned are due to anthropogenic climate change, we need a model of how area burned would be expected to change in response to greenhouse gas and sulfate aerosol changes, and its internal variability in the absence of such forcing. No coupled climate models incorporating forest fires have yet been run for historical forcing scenarios, though work is currently in progress to develop such models (V. Arora, personal communication, 2004). However, we may use a statistical model to estimate variations in area burned from simulated temperatures [*Flannigan et al.*, 2004]. We used the following regression model to represent variations in observed five year total area burned, $\mathbf{B_{o5}}$:

$$\mathbf{B_{o5}} = \beta_B\{5\hat{\alpha}(\mathbf{T_{m5}} - \mathbf{v})\} + \mathbf{w} \qquad (2)$$

where $\mathbf{T_{m5}}$ is a vector of five year mean area-burned-weighted temperature anomalies simulated in response to greenhouse gas and sulphate aerosol increases, and β_B is the regression coefficient to be estimated. $\hat{\alpha} = \mathbf{T_{o1}^T B_{o1}}/\mathbf{T_{o1}^T T_{o1}}$, is the regression coefficient of observed annual area burned ($\mathbf{B_{o1}}$) against observed annual area-burned-weighted temperature ($\mathbf{T_{o1}}$), both expressed as anomalies from five year means, in order to ensure independence from the detection result using five year mean temperature. The factor of five scales annual area burned to five year total area burned. The properties of the internal variability in the model-simulated response, **v**, are estimated as before from variability in control temperature anomalies. The internal variability in the five year total area burned observations, **w**, is assumed to have five times the variance of observed interannual variations in area burned, $\mathbf{B_{o1}}$ (the serial correlation of these annual area burned anomalies is only 0.03, thus this is a reasonable assumption). This results in synthetic reconstructions of internal variability with a 5–95% range of ±0.53 × 10^5 km^2 (shown by the dashed lines in Figure 2). A detection and attribution analysis was then applied to the 1920–1999 observed variations in area burned using this model.

[10] The regression coefficient using area burned is shown with its uncertainty interval in Figure 3. The estimated value of β_B is inconsistent with zero, and therefore the influence of anthropogenic climate change on Canadian forest fires is detected using this model. The uncertainty range on β_B is consistent with one, although the best guess value is somewhat larger, suggesting that area burned varies more with temperature on decadal timescales than it does on interannual timescales. Although the residual test indicates that the model provides an adequate fit to the area burned observations, we know that our model of internal variability lacks physical processes which may contribute to the variance on longer timescales, thus these results should be interpreted with caution: If a physical processes other than

climate is inducing a trend in area burned without contributing to variance on shorter timescales, it may bias our results. Nonetheless, taken together with the robust detection of an anthropogenic influence on Canadian fire season temperatures, these findings suggest that anthropogenic climate change has contributed to the recent trend toward increasing area burned.

3. Conclusions

[11] Overall, in common with previous studies [*Van Wagner*, 1988; *Skinner et al.*, 1999, 2002; *Podur et al.*, 2002; *Stocks et al.*, 2003], our analysis demonstrates that there has been a pronounced upward trend in area burned by wildland fires in Canada over the past three decades. Since satellite observations began in the early 1970s reporting of forest fires has been relatively complete [*Stocks et al.*, 2003], so the increase is unlikely to be purely an artifact of changing reporting practices. Over the same period, Canada has experienced a warming during the fire season, and variations in temperature were found to explain much of the variability in area burned. Using output from the CGCM2 model, we demonstrate that these observed temperature changes are consistent with a response to anthropogenic greenhouse gas and sulfate aerosol emissions over the past eighty years. Using a statistical model to predict area burned based on climate model output, we further detect the influence of anthropogenic climate change on area burned itself. Thus our results suggest that predicted increases in Canadian forest fire occurrence due to anthropogenic climate change [*Wotton and Flannigan*, 1993; *Stocks et al.*, 1998; *Flannigan et al.*, 2004] are already being observed. This increase in fire occurrence is likely to have important implications for terrestrial carbon dioxide emissions [*Kurz and Apps*, 1999; *Amiro et al.*, 2001], as well as for forest ecosystems and the forest industry [*Weber and Flannigan*, 1997].

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