PREDICTING THE EFFECTS OF CLIMATE CHANGE ON FIRE FREQUENCY IN THE SOUTHEASTERN CANADIAN BOREAL FOREST

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Abstract. Although an increasing frequency of forest fires has been suggested as a consequence of global warming, there are no empirical data that have shown climatically driven increases in fire frequency since the warming that has followed the end of the "Little Ice Age" (~1850). In fact, a 300-year fire history (AD 1688–1988) from the Lac Duparquet area (48°28'N, 79°17'W) shows a significant decrease both in the number and extent of fires starting 100 years ago during a period of warming. To explore this relationship between climatic change and fire frequency we used daily data from the Canadian Atmospheric Environment Service's General Circulation Model to calculate components of the Canadian Forest Fire Weather Index (FWI) System for the $1 \times CO_2$ and $2 \times CO_2$ scenarios. The average FWI over much of eastern Canada, including the Lac Duparquet region, decreased under the $2 \times CO_2$ simulation, whereas FWI increased dramatically over western Canada. According to these results, fire frequency would decrease over the southeastern boreal forest which is in agreement with the empirical data from the fire history. Our results stress the importance of large regional variability and call into question previous generalisations suggesting universal increases in the rate of disturbance with climate warming.

Keywords. BOREAL FOREST, WILDFIRE, CLIMATE CHANGE, GCM.

1. Introduction

Whether or not it is related to the 'Greenhouse Effect', an increase in temperature has already been observed in the northern hemisphere. Abrupt change in tree radial growth (Payette *et al.*, 1985; Fritts, 1991; Archambault and Bergeron, 1992), glacier recession (Luckman and Osborn, 1979; Luckman, 1988) and tree-line fluctuations (Scott *et al.*, 1987) have been attributed to increasing temperatures since the end of the Little Ice Age (~1850). For the last century, many historical climate analyses (Boden *et al.*, 1990) point to an increase of about 0.6 °C in the global mean temperature. Rising temperatures were observed from the 1880s until the 1940s which was followed by a cooling to the mid-1960s and a warming since 1970 which now exceeds the 1940s level. For Canada, a significant warming has occurred which has been most pronounced over the Mackenzie district where the mean temperature has risen 1.7 °C during the last century (Environment Canada, 1992).

Climatic change and its effects on forest disturbance dynamics is presently a major concern. In the boreal forest, fire is a major disturbance (Payette, 1992) and a change in fire regime resulting from climatic change might have a greater impact on the forest that climatic change *per se*.

Although variations in fire frequency driven by climate change have been reported for the Holocene (Filion, 1984; Clark, 1990; Johnson and Larsen, 1991), the effect of recent warming on fire frequency has proven difficult to document. Decreases in fire frequency during the last century were observed in many studies (Heinselman, 1973;

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Cwynar, 1977; Van Wagner, 1988), however, the timing of these decreases corresponds to an increase in human activities and they were attributed to fire suppression.

Recently, Bergeron (1991) reported a decrease in fire frequency on islands on Lac Duparquet in the southern boreal forest of Quebec. Fire frequency during the period between 1870 and 1989 was 34% lower than in the preceding 74 years. The observed decrease was attributed to changes in the climate because fires are not suppressed on the islands and fires were shown to be locally ignited. More recently Bergeron and Archambault (1993) using a dendroclimatological approach attributed this decrease to a reduced frequency of drought periods conducive to fire. Since climate may control fire regimes over large areas, they suggested that the decrease in fire frequency would have affected all the Quebec southern boreal forest fringe.

These empirical results contrast with the predicted effects of climate warming. An increasing rate of forest disturbances, including fires, has been postulated (Overpeck *et al.*, 1987). Based on twentieth century climate data, Clark (1988), postulated that the warming should have brought about an increase in fire frequency for Minnesota. For Canada, Flannigan and Van Wagner (1991) predicted a possible 46% increase in seasonal fire severity rating, with a possible similar increase in area burned in a $2\times CO_2$ climate. These contradictory results between observed and predicted effects call into question the accuracy of the models to predict fire danger or may be indicative of large regional variability in response to climate change.

Using the daily data from the Canadian Atmospheric Environment Service's General Circulation Model we present here simulations predicting the components of the Canadian Forest Fire Weather Index (FWI) System for the $1\times CO_2$ and $2\times CO_2$ scenarios. Our objective is to compare the modelled results with field data on fire frequency from the southeastern boreal forest (Lac Duparquet region). Further, we will investigate the hypothesis suggested by Bergeron and Archambault (1993) that warming may lead to a decrease in drought periods conducive to fires in the southeastern boreal forest. Additionally, we briefly evaluate regional variation of the components of the FWI System across Canada under the $2\times CO_2$ scenario.

2. Methods

The Canadian General Circulation Model (GCM) was used in this study to evaluate the effect of climate change on the fire regime. This model has a transform grid spacing of 3.75° by 3.75° with upgraded physics including full diurnal and annual cycles (Boer *et al.*, 1992, McFarlane *et al.*, 1992). Daily data rather than monthly data were used in this study as the fire regime can change dramatically over time periods much shorter than a month. The Canadian GCM was selected because of the availability of daily data. Temperature, specific humidity, precipitation and wind speed were obtained every 12 h (0000 and 1200 GMT) for 9 years for the $1\times CO_2$ and $2\times CO_2$ simulations. The specific humidity was converted into relative humidity. We used the maximum daily temperature, relative humidity, 24 h precipitation and the 12 h (1200 GMT) mean wind speed to calculate components of the Canadian Fire weather Index (FWI) System (Van Wagner, 1987) during the fire season (01 April to 31 October). The Fire Weather Index System comprises three fuel moisture codes and three fire behaviour indexes.

The three moisture codes represent the Fine Fuel Moisture Content (FFMC), loosely compacted organic matter (Duff Moisture Code) and the deep layer of compact organic matter (Drought Code). The three fire behaviour indexes, which are derived from the moisture codes and the surface wind speed, indicate the rate of initial fire spread (Initial Spread Index), total available fuel (Build Up Index) and the intensity of spreading fire (Fire Weather Index). Components of the FWI System were calculated for both simulations and then compared by taking the ratio of 2×CO_2 divided by 1×CO_2. Extreme maximums in addition to the mean values for the 9 years of the FWI components were used in this analysis. Extremes were used in this study because only a few days with extreme fire weather conditions are responsible for most of the area burned by forest fires. The importance of extremes is another reason to use daily GCM data as opposed to monthly data. Comparisons of the meteorological variables used in the calculation of the FWI components were done between the 1×CO_2 and 2×CO_2 simulations. Transient conditions that would occur between the two simulations were not addressed in this study. To test the hypothesis of Bergeron and Archambault (1993) who suggest the number of drought periods are reduced in a warmer climate we calculated the number of days with precipitation greater than or equal to 1.5 mm from the two data sets. We used this threshold as values less than 1.5 mm would be intercepted by the canopy (Rutter, 1975).

3. Results and Discussion

The FWI System is calculated by combining temperature, relative humidity, 24 h precipitation and the wind speed. Figure 1 shows the increase in mean temperature for Canada between the 2 simulations (2×CO_2 – 1×CO_2). Most of Canada including the Lac Duparquet region show increases of 3–4 °C. Temperature increases considered alone will lead to higher FWI values. The ratio (2×CO_2/1×CO_2) of precipitation amounts (Figure 2) and relative humidity (not shown) show that precipitation and relative humidity increase (ratio greater than 1.00) over our study area. Increases in precipitation and relative humidity will lead to decreases in FWI. Mean wind speed is essentially unchanged between the two runs. From the response of the input weather variables for the calculation of the FWI (temperature, precipitation, relative humidity and wind speed) to the projected climatic change (2×CO_2) it is unclear which trend (increasing FWI due to increasing temperature or decreasing FWI due to increasing precipitation and relative humidity) will prevail.

The 9 year average FWIs across Canada were calculated for the 1×CO_2 and 2×CO_2 simulations (not shown). In terms of validation for the FWI data, the relative pattern for the 1×CO_2 simulation is similar to a map of FWI across Canada (Simard, 1973) which was prepared using actual observations from 364 stations for 10 years (1957–66), although our absolute values are lower than those calculated by Simard. Our results for the mean FWI calculated from the 1×CO_2 scenario were compared against the mean FWI values calculated using observations for 29 stations across Canada for the period 1953–80 (Harrington *et al.*, 1983). The mean FWI calculated from the 1×CO_2 simulation were reasonably well correlated with the observed mean FWI (correlation coefficient 0.66) and we feel that the FWIs from the simulation are a reasonable approximation of the recent past. Figure 3 shows the ratio of the 2×CO_2 values

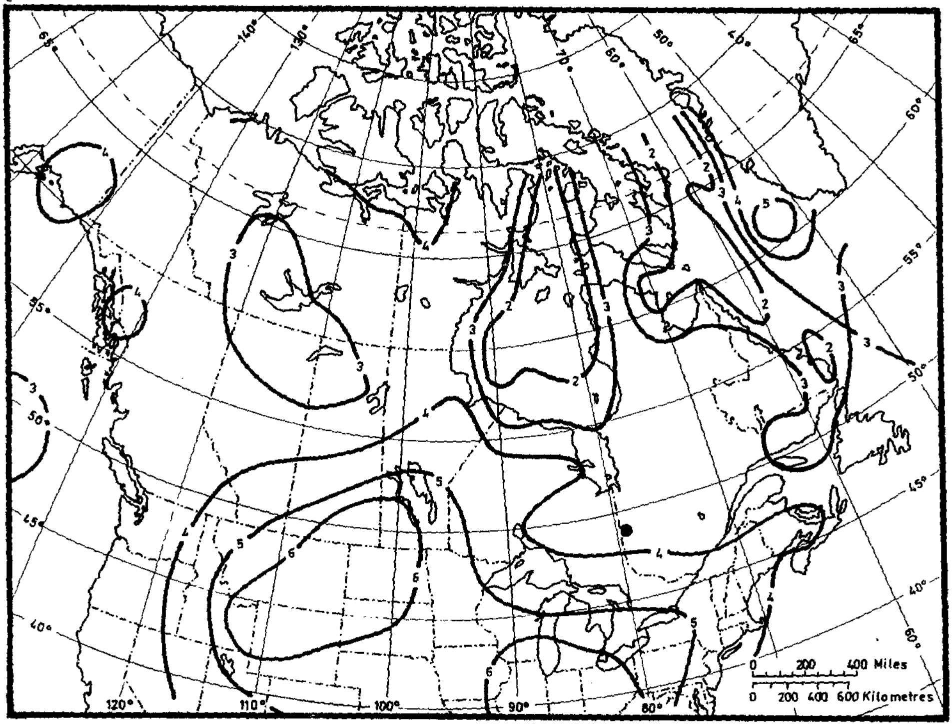

Fig. 1. Mean temperature (°C) for $2\times CO_2$ – $1\times CO_2$ simulations. The black dot (●) indicates the location of Lac Duparquet on all the figures.

divided by the 1xCO2 values. Much of eastern Canada, including the Lac Duparquet region, has a ratio below 1.00 (Figure 3) indicating that the FWI has decreased despite the warmer temperatures associated with the $2\times CO_2$ climate. The ratio of extreme maximum values of the FWI (not shown) for the 9 year period have a similar pattern to Figure 3. The other components of the FWI System show similar results to those shown in Figure 3.

The FWI represents the intensity of a spreading fire. Thus, lower intensity fires would on average yield reduced area burned given everything else remains unchanged (ignition agents, fire suppression activities etc.). Increasing fire severity would be anticipated with increasing temperatures if the other factors such as relative humidity, wind speed and precipitation amount remain unchanged. Precipitation amounts and relative humidity are somewhat higher over the Lac Duparquet region in the $2\times CO_2$ simulation as compared to the $1\times CO_2$ (Figures 1 and 2) which has more than offset any increases in the FWI due increased temperature. These results differ from those obtained from Flannigan and Van Wagner (1991) who found an increase in seasonal fire severity rating (a derivative of the FWI) at 6 stations across Canada. However, that study used monthly anomalies from three GCMs (Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS), and Oregon State University (OSU)) whereas the present study used daily GCM data from the Canadian GCM.

Figure 4 shows the difference in the number of days in June with precipitation over 1.5 mm for the two model runs. The month of June was selected as it has the most fire

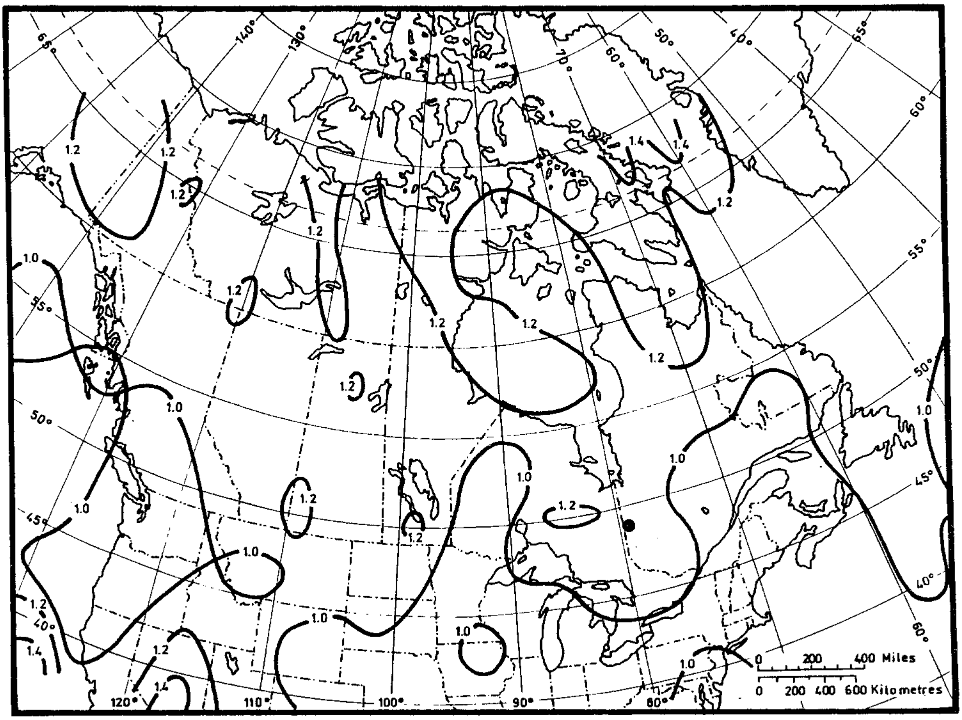

Fig. 2. Precipitation ratio ($2\times CO_2$ /$1\times CO_2$).

activity for northwestern Quebec (Harrington, 1982). There are almost 2 more days of precipitation per month for the $2\times CO_2$ simulation at this location. This result lends credence to the hypothesis that the fire frequency can be reduced even in a warmer climate if there are fewer periods of drought. Flannigan and Harrington (1988) have demonstrated a link between area burned and frequency of drought.

Fire activity is often linked to the location of the upper ridge associated with warm and dry conditions at the surface (Newark, 1975). Conversely, there is a lack of fire activity associated with upper troughs that usually result in wet and cool conditions at the surface. Given the variation in wavelengths in the upper flow at least one ridge and one trough are typically found over North America during the summer. On average the upper ridge is found over western North America typically running along the west coast and an upper trough is found over eastern North America anchored over Hudson's Bay. (This is an average position, a great deal of variability is found on daily weather charts.) In a warming climate the upper ridge would be expected to amplify while the trough would weaken. The trough would remain anchored over Hudson's Bay because of the relatively cold temperatures associated with this large water body. (This is consistent with the results shown in Figure 1 showing much lower temperature increases over Hudson's Bay.) A weakening of the upper trough over eastern Canada would probably result in the northward movement of the polar front. This would allow more frequent incursions of a warm and humid airmass. This would lead to higher relative humidity and more precipitation which is consistent with our results. Thus, a

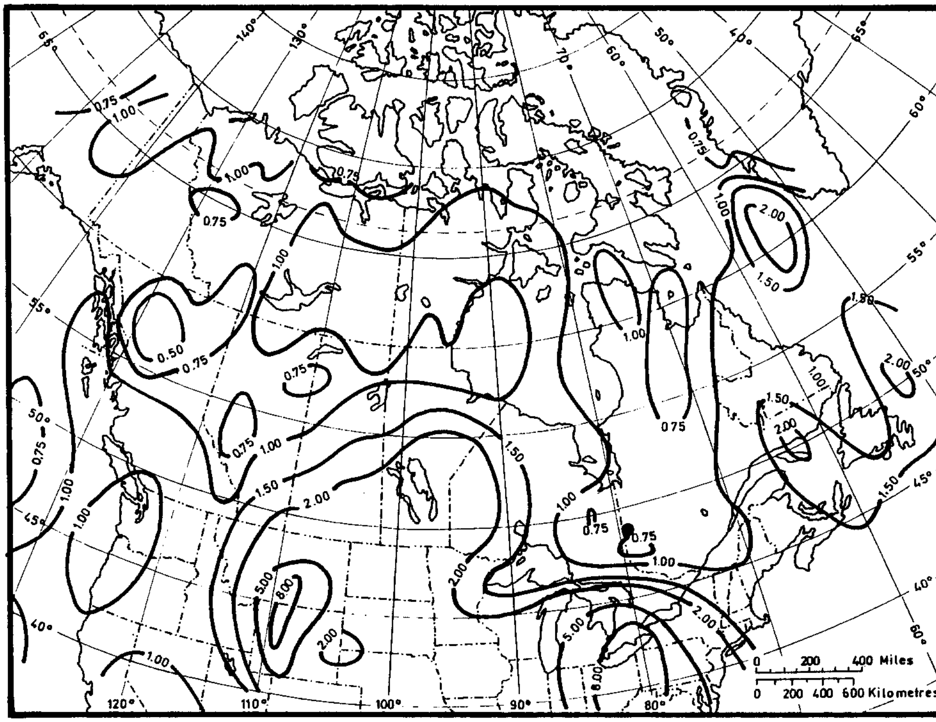

Fig. 3. FWI ratio ($2\times CO_2 / 1\times CO_2$).

reduced frequency of drought periods would be anticipated which would inhibit fire ignition and spread and has already been observed in the last 100 years over the southern boreal forest in the Lac Duparquet area. However, this relationship between warming and decreased frequency of drought found in the recent past and suggested by the GCM does not preclude the possibility that warmer and drier conditions can occur.

Climatic warming would allow many species to extend their range limits northward (Liu, 1990; Solomon, 1986). This would mean that the southern boreal forest might be replaced by many species that are currently found in the present day mixed-wood forest (Rizzo and Wiken, 1992). This area would be available for expansion because of the warmer climate or because of the change to a less severe fire regime. The change in vegetation may alter the fire regime as many of the broad leaved tree species of the mixed woods forest are not predisposed to fire. The possible decrease of fire frequency over the boreal forest may hasten vegetational change as the boreal forest has been maintained by semi-regular fire occurrence. Red pine (*Pinus resinosa* Ait.) and white pine (*Pinus strobus* L.) may increase in abundance as fire intensity decreases. Bergeron and Dubuc (1989) suggest that if disturbance frequency is reduced eastern white cedar (*Thuja occidentalis* L.) and balsam fir (*Abies balsamea* (L.) Mill.) would also increase in abundance.

While these results indicate a reduced FWI over the Lac Duparquet region the results also highlight a large regional variation across Canada. We will restrict our discussion to non-mountainous regions of Canada as the GCM grid is too coarse to

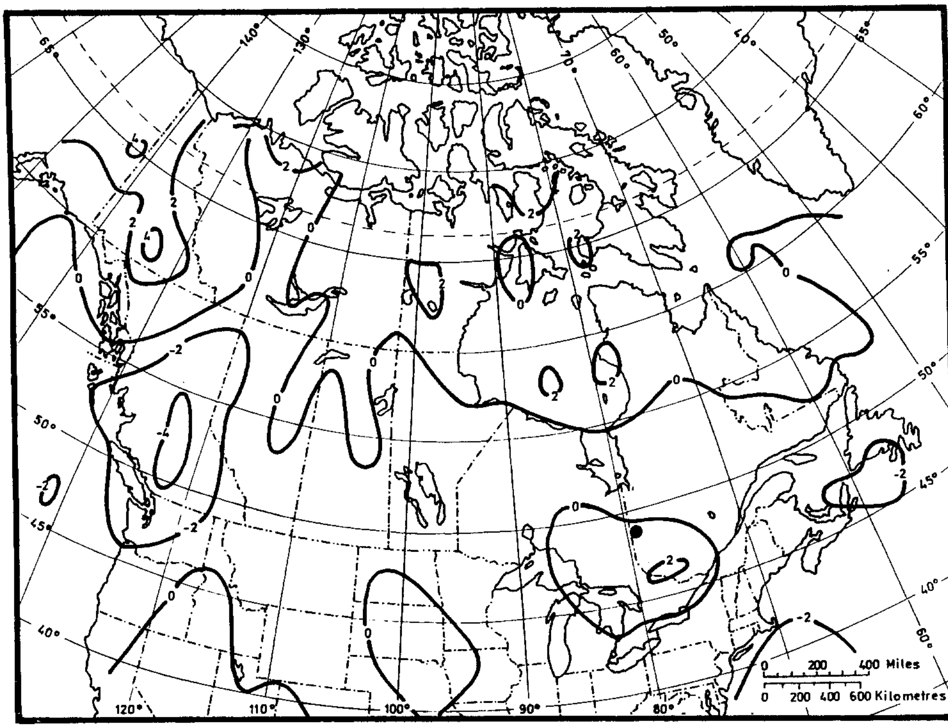

Fig. 4. Number of days in June with precipitation of 1.5 mm or greater from the simulations ($2{\times}CO_2$ - $1{\times}CO_2$).

obtain credible estimates for mountainous areas. The most striking feature of the regional variation is the dramatic increase in FWI (Figure 3) and all the other FWI components with the climatic change over central Canada. These results do corroborate some aspects of the results of other studies that suggest increased disturbance with climate warming (Flannigan and Van Wagner, 1991; Overpeck *et al.*, 1990). These increases in the FWI occur over western Canada where historically most of the fire activity occurs (Harrington, 1982; Higgins and Ramsey, 1992). Therefore, if fire intensities decrease where fire is a relatively minor problem, such as eastern Canada, and fire intensities increase where fire can be a major problem, such as western Canada, then climate change can still result in dramatic changes in the fire regime on a continental scale.

4. Summary

Results from our simulations are consistent with field data collected in the southeastern boreal forest that indicate a decrease of fire frequency with climate warming. Our results also support the hypothesis of Bergeron and Archambault (1993) that climatic change may lead to a decrease in drought periods in the southeastern boreal forest. Finally, it is clearly evident from this study that there is a large regional variation in the components of the Fire Weather Index and that some regions show a decrease in the FWI.

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