

FIRE WEATHER: PAST, PRESENT AND FUTURE

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SUMMARY

This study examines the fire weather in the past, present and future. Three approaches are used. First, we used the Canadian GCM to model the present and future fire weather by calculating the FWI System indexes for the 1xCO₂ and 2xCO₂ simulations. Second, we calculated the FWI System indexes 6 000 years ago (6ky B.P.) as well as the present day using a specially modified version of the Canadian GCM. Lastly, a record of anomalies in the charcoal record, indicating relative changes in fire activity, was calculated for 6ky B.P. in ca. 19 lakes from Quebec. The anomalies are computed per lake and calculated by comparing the net accumulation rate for 6ky B.P. as compared to the average charcoal accumulation rate for the post-glacial forest period as well as the last 1000 years. Additionally, charcoal data from across northern North America are used to compare fire activity at 6ky B.P. to present day. Results showed good agreement between the historical modelling and the charcoal record and suggests that the mid-Holocene period may be a suitable analogue for predicted climate change in the next century.

INTRODUCTION

Fire and climate are closely linked (Swetnam 1993). According to simulations of various general circulation models (GCMs), the Earth's climate will be 1-3.5 °C warmer (Intergovernmental Panel on Climate Change (IPCC) 1996) by the end of the next century due to increasing atmospheric concentrations of radiatively active gases such as carbon dioxide, methane, nitrous oxides and the chloroflourocarbons. These changes in the climate will result in changes in the day to day weather that influences forest fires. Fire is an important factor in the vegetation dynamics of Canadian forests, in particular, the boreal forest. On average, over 2.5 million ha of forest are burned every year in Canada. Typically, a few large fires are responsible for most of the area burned (3% of the fires are responsible for 97% of the area burned). Most of the fire activity occurs during a few days with severe fire weather.

How will the fire weather respond to the so-called greenhouse warming? Many believe that increases in temperature will lead to increased fire weather severity and to increased area burned (Overpeck et al. 1990). However, fire is strongly dependent on other weather variables as well, such as precipitation, wind speed and relative humidity. In this study we will use the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) to estimate the forest fire danger. This system uses temperature, precipitation, wind speed and relative humidity as meteorological inputs.

Three approaches are used in this study on fire weather. First, we used the Canadian GCM to model the present and future fire weather by calculating the FWI System indexes for the 1xCO₂ and 2xCO₂ simulations. Second, we modelled the fire weather 6 000 years ago (6 ky B.P.) as well as the present day using a specially modified version of the Canadian GCM. Once again the output from these simulations were used to calculate the FWI System indexes. The third approach was to use the charcoal record to give an indication of the fire activity during the Holocene. Two methods were employed. The first method was the analysis of charcoal in lake sediments from 19 sites in Quebec. The second method surveyed the paleoecology literature for charcoal records from across Canada and nearby sections of the United States. The objective of this study is to examine the fire weather in the past, present and future. These approaches will allow us to comment on the future fire weather relative to the present day and to conditions 6 ky B.P.. We are using the 6ky B.P. as a reference because this was a period that was warmer than present day (Wright et al. 1993), and might be an

analogue for future warming. The charcoal record gives us an indication of the fire incidence during the Holocene and is an independent means to validate the 6ky B.P. simulation.

METHOD AND DATA

To model the fire weather we used the Canadian Fire Weather Index (FWI) System and in particular we used the Fire Weather Index (FWI) which represents the intensity of a spreading fire. In this study, we used the Canadian GCM to model the present and future FWI and to evaluate the impact of climate change on the fire weather. The Canadian GCM has a transform grid spacing of 3.75° by 3.75° with full diurnal and annual cycles (Boer et al. 1992; McFarlane et al. 1992). Daily data, rather than monthly data, were used because the fire weather can change dramatically over time periods much shorter than a month. Temperature, specific humidity, precipitation and wind speed were obtained every 12h (0000 and 1200 GMT) for 9 years for both the $1\times\text{CO}_2$ and $2\times\text{CO}_2$ simulations. We used the maximum daily temperature, relative humidity derived from the specific humidity, 24 h precipitation and the 12 h (00 GMT) mean wind speed to calculate components of the Canadian FWI System during fire season. We defined the fire season as May 1 to August 31. The FWI was calculated for both simulations and then compared by taking the ratio of $2\times\text{CO}_2$ to $1\times\text{CO}_2$. Extreme FWI maximums, in addition to the mean values for the 9 years were used in this analysis. Extremes were used because most of the area burned is a result of a few days with extreme fire weather conditions (Flannigan and Harrington 1988).

The procedure outlined above was also used to generate the mean and extreme maximum FWI for 6ky B.P. and for present day. To generate the 6ky B.P. and present day simulations the Canadian GCM was modified by changing the orbital parameters and the carbon dioxide levels to be appropriate for 6ky B.P. and present day.

A Lacustrine Charcoal Data-base covering the Quebec region, (Department of Geography, University of Montreal) is used to reconstruct the spatial pattern of fire occurrence in Quebec at 6ky B.P. Only 19 lakes from Quebec region with surface areas smaller than 10 ha (average 3.5 ± 2.4 ha) have been included. To reduce differences in charcoal taphonomy between sites, peats and large lakes have been excluded. (Table 1). Furthermore, sites which were not yet forested at 6ky B.P. have been excluded. No sites

above 49°N are available due to the presence of the residual Laurentide Ice-sheet and tundra vegetation 6ky B.P. (Richard 1995). We have also excluded lakes with chronologies based on fewer than three ^{14}C dates, to ensure correct estimates of charcoal accumulation rate (CAR). CAR is essential to computing fire occurrence. An average of 5.7 ± 2.0 ^{14}C dates per site were available. For each site, the age/depth model is based on the ^{14}C dates as calibrated using CALIB program (Stuiver and Reimer 1993). A curvilinear interpolation of dated levels allows the computation of age/depth models on which the calculation of the sediment accumulation rate ($\text{cm}\cdot\text{yr}^{-1}$) are based.

Sediments were processed for pollen analysis (Faegri and Iversen 1989). Microscopic pieces of charcoal were measured using an ocular grid (Swain 1973). An exotic pollen (Eucalyptus) suspension was added to each sample in order to determine the charcoal concentration per volume of sediment ($\text{mm}^2\cdot\text{cm}^{-3}$), then the CAR, given in $\text{mm}^2\cdot\text{cm}^{-2}\cdot\text{yr}^{-1}$. The mean time resolution of the charcoal analysis at 6ky B.P. is about 3.6 samples/1000 years (minimum of 2 samples/1000 years). This coarse resolution is the result of the research for which the data were initially collected, i.e., the general post-glacial vegetation history of the Quebec region (Richard 1977, 1993, 1994).

CAR curves show mean and maximum absolute values highly varying from site to site. These variations probably result from the size and the physiography of the individual lake's catchment area, from the vegetation type (flammability, combustibility and fuel load), and from the severity of the fire regime. Because the intersite variability is important, we focused the analysis on long-term trends in charcoal influx and calculated CAR anomalies. An anomaly corresponds to the difference between the mean CAR values from 5.5 to 6.5 ky B.P. versus the present CAR (defined as the mean CAR between 0-1 ky B.P. This allows comparison with the COHMAP computer-simulated climatic data (Wright et al. 1993). A second calculation of anomalies compares the 5.5-6.5 ky B.P. period to the mean of the entire forested period at a given site, and is referred to as the Post-Glacial Forest (PGF) anomaly set. This set includes a varying time period at each site, but may reduce some taphanomical differences between sites. A negative anomaly (-) corresponds to a low regional occurrence of fire and vice versa for positive anomaly (+); anomalies are recorded as null (0) if less than one half of the standard deviation of CAR in the core as a whole.

The scattered charcoal influx diagrams show a log-normal distribution. To apply t-tests require a normal distribution, the raw CAR values have been transformed by using their natural logarithm (Jongman et al. 1995) before calculation of the means.

Table 1: Characteristics of sites with fire occurrence records at 6ka \pm 500 years in Quebec area. Modern and 6ka vegetation is given according to Richard (1995). "Mixed": mixed-deciduous forest or cool temperate forest dominated by *Abies balsamea*, *Acer rubrum*, *A. saccharum*, *Betula alieghaniensis*, *Fagus grandifolia*, *Pinus resinosa*, *P. strobus*, *Tilia americana*, *Tsuga canadensis*. "Boreal": closed boreal forest or southern boreal forest dominated by *Abies balsamea*, *Betula alieghaniensis*, *B. papyrifera*, *Picea glauca*, *Picea mariana*, *Pinus banksiana*, *P. resinosa*, *P. strobus*, *Populus tremuloides*, *Thuja occidentalis*. "Taiga": open boreal forest or northern boreal forest dominated by *Picea mariana*, *Pinus banksiana*. Anomalies positive (+), null (0), and negative (-) according to the period of reference, i.e., 0.5ka \pm 500 years or the entire post-glacial forest (PGF) period per site. **, *** indicate that t test were significant at $p < 0.1$, 0.05 , 0.01 respectively. "nr": no period of reference due to a lack of data at 0.5ka.

| Lake | Latitude (°N) | Longitude (°W) | Elevation (m) | Modern and 6ka veg. | Lake surface (ha) | Number of 14C dates | 0.5ka | Forest Period |
|--------------|------------------|-------------------|------------------|---------------------------|-------------------------|------------------------|-------|------------------|
| Albion | 45°40'15" | 71°19'30" | 320 | Mixed | 2.5 | 7 | - | 0 |
| Atocas (aux) | 45°32'34" | 73°18'39" | 114 | Mixed | 1.2 | 4 | + | 0 |
| Bouchard | 48°56'14" | 64°35'52" | 145 | Boreal | 3.5 | 8 | *** | - |
| Caribou | 48°11'52" | 64°56'24" | 116 | Boreal | 2.6 | 7 | + | 0 |
| Castor | 46°36'50" | 72°59'56" | 220 | Mixed | 0.1 | 6 | nr | 0 |
| Clo | 48°29'49" | 79°21'10" | 280 | Boreal | 0.7 | 3 | nr | - |
| Desautels | 49°27'28" | 73°15'00" | 480 | Taiga | 3.0 | 5 | 0 | 0 |
| Dolbeau | 48°58'01" | 65°57'21" | 965 | Boreal | 3.1 | 7 | *** | - |
| Flévy | 48°13'01" | 71°13'08" | 381 | Boreal | 1.5 | 3 | + | 0 |
| Gabriel (St) | 46°16'33" | 73°28'33" | 250 | Mixed | 0.3 | 6 | 0 | 0 |
| J'Arrive | 49°14'50" | 65°22'35" | 56 | Boreal | 2.4 | 6 | *** | - |
| Léonard | 49°12'28" | 65°48'46" | 17 | Boreal | 0.2 | 5 | 0 | 0 |
| Madeleine | 47°40'20" | 70°43'10" | 800 | Boreal | 8.3 | 4 | 0 | 0 |
| Main | 47°42'00" | 70°37'20" | 730 | Boreal | 9.6 | 6 | nr | 0 |
| Neume | 47°35'16" | 77°06'39" | 363 | Boreal | 2.9 | 5 | 0 | - |
| Ouellet | 47°31'58" | 68°56'38" | 300 | Mixed | 0.6 | 3 | - | - |
| Perdu | 49°10'15" | 66°19'25" | 152 | Boreal | 0.5 | 11 | 0 | 0 |
| Spearman | 46°32'38" | 78°30'10" | 368 | Mixed | 3.1 | 5 | + | 0 |
| Yamaska | 45°27'28" | 72°52'19" | 265 | Mixed | 0.2 | 7 | *** | - |

Of the 19 sites in this compilation, 3 lakes do not show enough data at $0.5\text{ka} \pm 500$ years to use this period as a reference.

Published data were used for Lac Louis and all 22 sites outside Quebec (Table 2). These sites were analyzed by various researchers over a period of 20 years, using a variety of methods. Most were analyzed by counting charcoal fragments larger than a certain size on pollen slides, either tallying the total area of fragments, the total number, or by point count. In several cases, the results are reported as a charcoal : pollen ratio. Two (published by Kuhry, 1994), used the frequency of visible charcoal horizons in peat cores. Two sites (including one in Wisconsin) were analyzed by chemical assay of charcoal content (Winkler, 1985, 1994; Campbell, 1998). At some sites, the sediment was sieved and large charcoal fragments weighed or tallied simply as present or absent (Hu et al., 1993; 1996).

The sites used were of varying surface area, depth, and morphological characteristics, and several peat sites are included. They include sites in the grassland as well as in the boreal, Great Lakes - St. Lawrence, and Carolinian forest zones. Several of the western Canadian sites are in the foothills or mountains of the western cordillera.

In all cases, a pollen-diagram style graph was the only available data. A visual, subjective estimate was made, comparing the charcoal influx rate at ca. 6 ky B.P. with that of the last 500 years. If the charcoal curve had a high level of noise, this was taken into account subjectively. Large isolated peaks in the charcoal curve were largely ignored as possible unique events or artefacts. Given these variations in the site characteristics and analytical methods in the data from outside Quebec, there may be some question as to the validity of using such disparate data sets. Despite these cautions, however, the geographic pattern of negative and positive anomalies is consistent. Most negative anomalies in this data set occur in the Quebec region, with western Canada showing a significant number of positive anomalies. The only exception is one negative anomaly in Alaska, which can be explained by the 'arrival of *Picea mariana* in the area after 4ky B.P. while it had arrived at the other Alaskan site by 6.5ky B.P. (Hu et al., 1996).

Table 2. Characteristics of charcoal data sources from the literature

| Name | Lat | Long | Elev. | Drainage Area | Depth | Modern veg. | 6K veg. | Type of site | area | #dates | Type of Analysis | Anomaly | Reference |
|------------------|-------|--------|-------|---------------|-------|---------------------------------------|---------------------------------------|--------------|------|--------|---------------------------------------|---------|---------------------------|
| Mendoza | 43:06 | 89:25 | 257 | 64000 | 24 | Oak savannah | Oak savannah | Lake | 3490 | 3 | Assay/ original area | + | Winkler 1985, 1994 |
| Decoy | 43:14 | 80:22 | 260 | 1 | 0.5 | Oak savannah | Oak savannah | lake | 0.42 | 5 | Measured on pollen slides | + | Szeicz and Macdonald 1991 |
| Everitt | 43:30 | 66:00 | n/a | n/a | n/a | maple | Hemlock | lake | n/a | n/a | Area counts on pollen slides | + | Green 1982 |
| High | 44:31 | 76:36 | 192 | n/a | n/a | mixed-wood Great Lakes - St. Lawrence | mixed-wood Great Lakes - St. Lawrence | lake | 2.5 | 8 | point count on pollen slides | 0 | Fuller 1997 |
| Graham | 45:11 | 77:21 | 381 | n/a | n/a | Great Lakes - St. Lawrence | Great Lakes - St. Lawrence | lake | 2.5 | 6 | point count on pollen slides | 0 | Fuller 1997 |
| Harp Wetland | 45:20 | 79:12 | 389 | n/a | 0 | Great Lakes - St. Lawrence | Great Lakes - St. Lawrence | Swamp | 1.2 | 6 | count on pollen slides | + | Bunting et al. 1996 |
| Perch | 46:02 | 77:21 | 156 | n/a | 3.5 | Great Lakes - St. Lawrence | Great Lakes - St. Lawrence | Lake | 45 | 1 | count on pollen slides | - | Terasmae and Weeks 1979 |
| Louis | 47:15 | 79:07 | 300 | n/a | 7.6 | Boreal | boreal | Lake | 25 | 3 | count on peels | + | Terasmae and Weeks 1979 |
| Richter Marsh | 49:01 | 119:30 | 450 | 30 | 0 | Grassland | grassland | Kettle marsh | 15 | 0* | count > 10 um on pollen slides | 0 | Cawker 1983 |
| Wabamun | 50:32 | 114:35 | 725 | 26000 | 10 | Boreal mixed-wood | boreal mixed-wood | lake | 8180 | 10* | count on pollen slides | + | Hickman et al. 1984 |
| Lone Fox | 56:43 | 119:43 | 1000 | n/a | 3 | boreal | boreal | Lake | 5 | 6 | point count on pollen slides | 0 | MacDonald 1987 |
| Klassen Bajada | 50:52 | 111:15 | 638 | 285 | 0 | grassland subalpine | grassland subalpine | Alluvial fan | 86 | 3* | assay count of charred microfossils | 0 | Campbell 1998 |
| O'Hara | 51:21 | 116:20 | 2015 | n/a | 42 | Alpine meadow | alpine meadow | lake | 50 | 3* | count > 30 um on pollen slides | + | Reasoner and Hickman 1989 |
| Wilcox Pass | 52:15 | 117:13 | 2355 | n/a | 0 | boreal mixed-wood | boreal mixed-wood | Bog | n/a | 2 | count > 3 um on pollen slides | 0 | Beaudoin and King 1990 |
| Smallboy | 53:35 | 114:08 | 782 | n/a | 7.5 | Boreal mixed-wood | boreal mixed-wood | lake | 1 | 6* | count > 3 um on pollen slides | + | Vance et al. 1983 |
| Mariana Lakes | 55:54 | 112:04 | n/a | n/a | 0 | Boreal mixed-wood | boreal mixed-wood | fen | 690 | 3 | sieving | + | Nicholson and V/R 1990 |
| Buffalow Narrows | 55:56 | 108:34 | n/a | n/a | 0 | boreal | boreal | fen | 300 | 3 | viable charcoal | + | Kuhny 1994 |
| Kogalak Plateau | 56:04 | 63:45 | 534 | n/a | n/a | Heath tundra | shrub tundra | lake | n/a | 5 | Horizons | - | Short and Nichols 1977 |
| Nain Pond | 56:32 | 61:49 | 91 | n/a | n/a | Lichen woodland | shrub tundra | lake | n/a | 8 | Slides | - | Short and Nichols 1977 |
| Toboggan | 50:46 | 114:36 | 1480 | 15 | 5 | open subalpine | pine parkland | lake | 0.5 | 7* | point count on pollen slides | + | MacDonald 1989 |
| Legend lake | 57:28 | 112:57 | n/a | n/a | 0 | boreal | boreal | Fen | 700 | 4 | viable charcoal | + | Kuhny 1994 |
| Farewell | 62:33 | 153:38 | n/a | n/a | 10 | Boreal | taiga | lake | 400 | 6 | Horizons | - | Hu et al. 1996 |
| Wien | 64:20 | 152:16 | n/a | n/a | 30 | Boreal | boreal | lake | 1200 | 8 | presence/absence of fragments >425 um | - | Hu et al. 1993 |
| Black Gum Swamp | 42:15 | 71:30 | 380 | n/a | 5 | hemlock | hemlock | Swamp | 10 | 7 | point count on pollen slides | 0 | Foster and Zebryk 1993 |
| GB2 | 55:06 | 75:17 | 300 | n/a | 5 | boreal | taiga | Lake | 5 | 4 | area count on pollen slides | - | Gajewski et al. 1993 |
| EC1 | 56:17 | 75:06 | 250 | n/a | 9 | taiga | taiga | Lake | 4 | 4 | area count on pollen slides | - | Gajewski et al. 1993 |
| LB1 | 57:55 | 75:37 | 200 | n/a | 10 | taiga | taiga | Lake | 3 | 4 | area count on pollen slides | - | Gajewski et al. 1993 |
| LR1 | 58:35 | 75:15 | 170 | n/a | 9 | shrub tundra | tundra | Lake | 2 | 4 | area count on pollen slides | - | Gajewski et al. 1993 |

n/a: not available

TBA: not given in principle publication; data might be obtainable from other sources

* dates inferred by correlation of pollen stratigraphy

^ includes two tephra

RESULTS AND DISCUSSION

Figure 1 shows the difference in mean daily maximum temperature in degrees C for $2\times\text{CO}_2$ to $1\times\text{CO}_2$ for the May 1 to August 31 period. The forested regions of Canada are expected to be 3 to 4° warmer than $1\times\text{CO}_2$. Figure 2 displays the difference in mean daily maximum temperature in degrees C for 6ky B.P. to present day. Similarly, the model indicates that the forested regions of Canada 6ky B.P. were about 1°C warmer than present. The patterns of temperature differences are similar in both figures though the temperature change is larger for Figure 1 ($2\times\text{CO}_2$ minus $1\times\text{CO}_2$). Caution should be used when using the results from mountainous regions like western North America as the resolution of the models is so coarse that the topography is not realistically incorporated. Regional Climate Models (RCMs) could be employed for mountainous regions as they have a much improved spatial resolution.

Figure 3 depicts the ratio of the mean FWI for $2\times\text{CO}_2$ over $1\times\text{CO}_2$. Ratios greater than 1.0 indicate increased FWI with greenhouse warming while ratios less than 1.0 indicate decreased FWI. The increase in FWIs is most pronounced over the center of the continent with values significantly greater than the $1\times\text{CO}_2$ simulation. However, there are regions in eastern and western Canada where the ratio drops below 1.00, which means the FWI is expected to decrease despite the warmer temperatures (Figure 1). Figure 4 shows the ratio of the mean FWI for 6ky over present day. The results are similar to those shown in Figure 3 with a large area of increased FWI over the center of the continent and decreased FWI over eastern Canada. Differences between the figures include regions of northwestern Canada where the $2\times\text{CO}_2$ over $1\times\text{CO}_2$ ratios show decreased FWI as opposed to increased FWI in Figure 4. Also, the increases in FWI were much larger with future warming simulations as opposed to the 6ky B.P. over present day FWI ratios.

Noteworthy is the spatial variability in the response of fire weather to increasing temperatures. Despite increasing temperatures the corresponding FWI does not necessarily increase. The reason is due to changes in the other elements in the FWI System calculations, namely, precipitation and relative humidity. In particular, increases in precipitation amount and frequency more than offset the increased temperatures in regions where the FWI has decreased. There is historical evidence that fire frequency has decreased despite warmer temperatures (Flannigan et al. 1998). Bergeron and Archambault (1993) found that fire frequency decreased in northwestern Quebec since the end of the Little Ice Age (~1850)

despite increasing temperatures. Figure 3 suggests that northwestern Quebec will continue to have decreasing FWI with increasing temperature (Bergeron and Flannigan 1995).

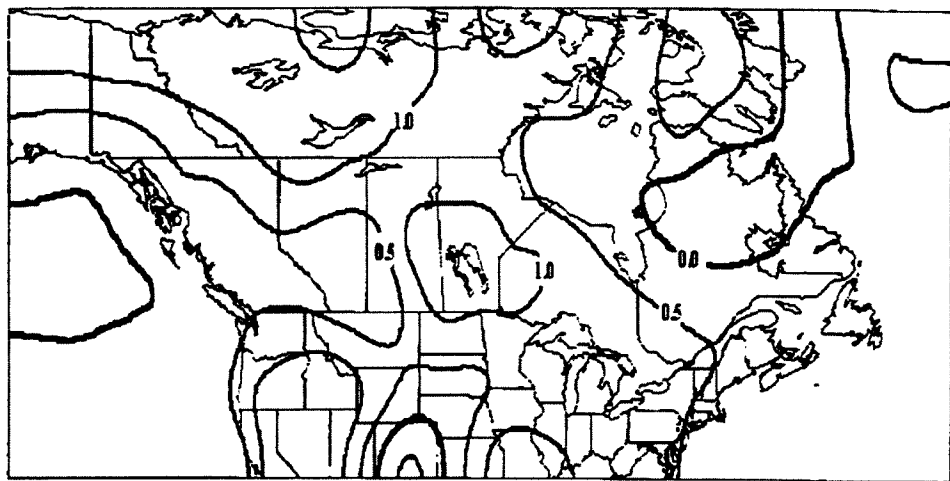


Figure 1 Mean Temperature change 6k - present (°C). The thick line is the 0°C isoline.

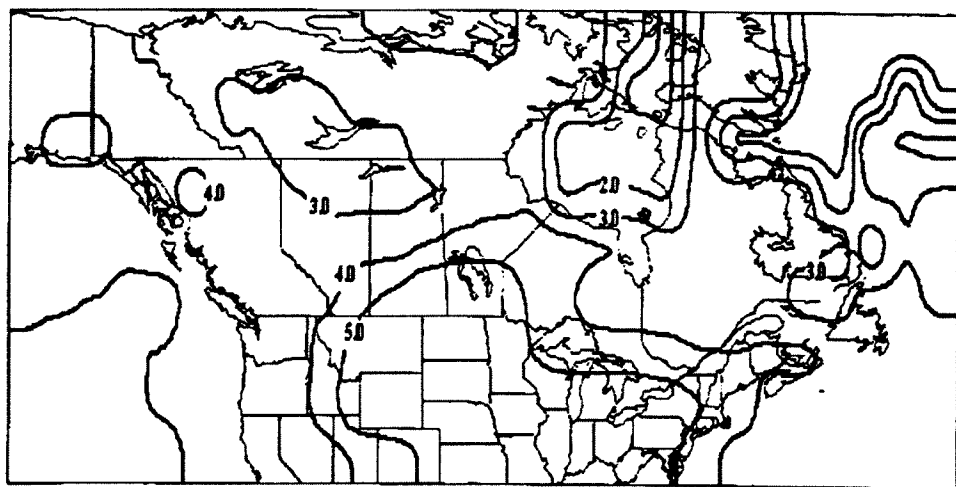


Figure 2. Mean Temperature change $2\times\text{CO}_2 - 1\times\text{CO}_2$.

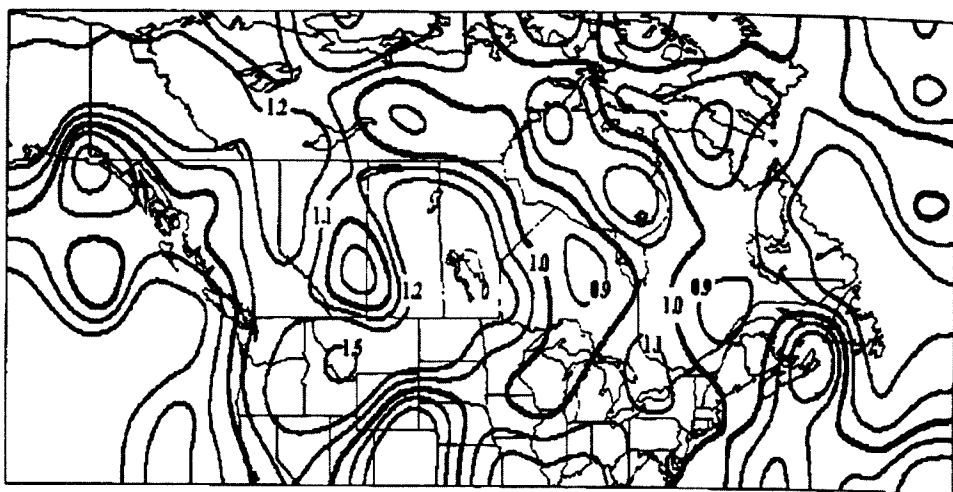


Figure 3. Mean FWI ratio (6k/present). Thick line is the 1.00 isoline.

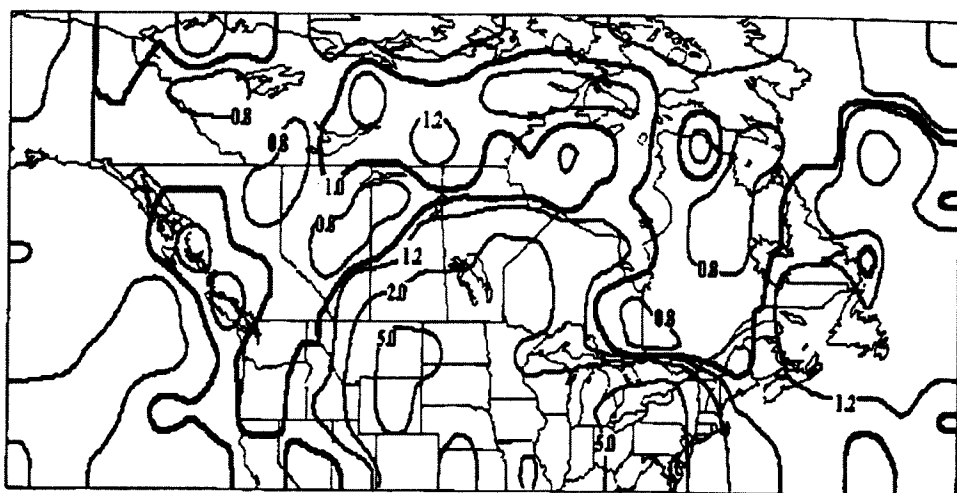


Figure 4. Mean FWI ratio ($2xCO_2 / 1xCO_2$).

The charcoal influx anomalies at 6ky B.P. from Quebec are characterized by a clear dominance of negative (-) values, whatever the reference period, i.e., last 1000 years or PGF. The vegetation zonation at 6ky B.P. does not seem to play a role in the fire occurrence according to the PGF period of reference. Only one site shows a positive anomaly, significant at 0.1: Atocas. Using the last 1000 years as reference, the mixed-deciduous forest which is

less flammable shows both negative (Albion, Ouellet, Yamaska) and positive (Atocas, Spearman) anomalies. Data from sites located within the boreal forest are characterized by negative anomalies, except Caribou and Flevy (Table 1).

The mapping of charcoal influx anomalies gives the regional tendency of fire occurrence. The analysis conducted at the scale of Quebec permits discussion of differences resulting from the vegetation pattern. Because (i) no vegetation-fire relationship is observed, (ii) the territory under consideration is large, and (iii) the data are homogeneous, the pattern of low regional fire occurrence must result from climate forcing.

Figures 5 and 6 show the anomalies in the charcoal data superimposed over the FWI ratio for 6ky over present (Figure 4) and for the FWI ratio $2\times\text{CO}_2$ over $1\times\text{CO}_2$ (Figure 5), respectively. Figure 5 shows that the historical modelled trend in the FWI agrees well with the spatial pattern of charcoal anomalies. Given the diverse means of determining the charcoal anomalies it suggests that charcoal analyses are quite robust. Excepting Northern Alberta, there is also a good fit between the projected fire weather (Figure 6) and the charcoal anomalies which suggests that the mid-Holocene might be a reasonable analogue for future warming. The reason for the poor fit in Northern Alberta could be due to the coarse resolution in the GCMs which can not properly resolve the Rocky Mountains. FWI simulations done with an RCM show increased FWIs in a $2\times\text{CO}_2$ world(not shown) for Northern Alberta which is what the charcoal anomalies would suggest.

What are the implications from these results in terms of fire activity? Forest fire activity is related to the FWI, as FWI increases we would expect increases in area burned. Harrington et al. (1983) found that the FWI System was correlated to area burned. From Figure 3 we would expect large increases in area burned by wildfire in the forests of Manitoba, eastern Saskatchewan and northwestern Ontario. At the southern edge of the forest the increased fire activity might lead to a more rapid transition from forest to grassland than expected from warming alone. Other areas like Quebec and northeastern Ontario might experience a reduction in area burned due to lower fire weather severity. There are other factors in addition to the weather that are affecting area burned such as landscape fragmentation, ignition agents, fire management activities, fire season length and the composition and structure of the vegetation. Most of the area burned by wildfire is the result of lightning-ignited wildfires. Indications are that lightning and lightning ignitions will increase in a $2\times\text{CO}_2$ climate (Price and Rind 1994). Also, Wotton and Flannigan (1993) have shown that the fire season length in Canada on average will increase by 22% or 30 days in a $2\times\text{CO}_2$

climate. Weber and Flannigan (1997) discuss in detail the implications of an altered fire regime due to climate change on the structure and function of the Canadian boreal forest.

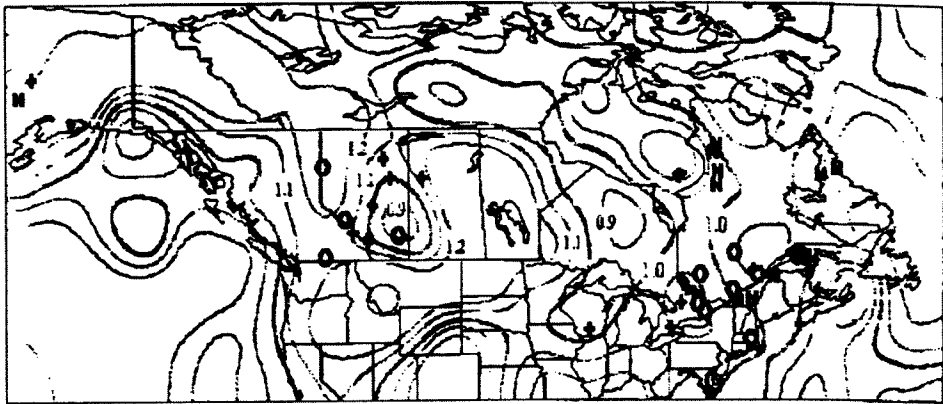


Figure 5. Charcoal anomalies superimposed on mean FWI ratio (6k/present) where + is a positive anomaly, O is no change and N is a negative anomaly.

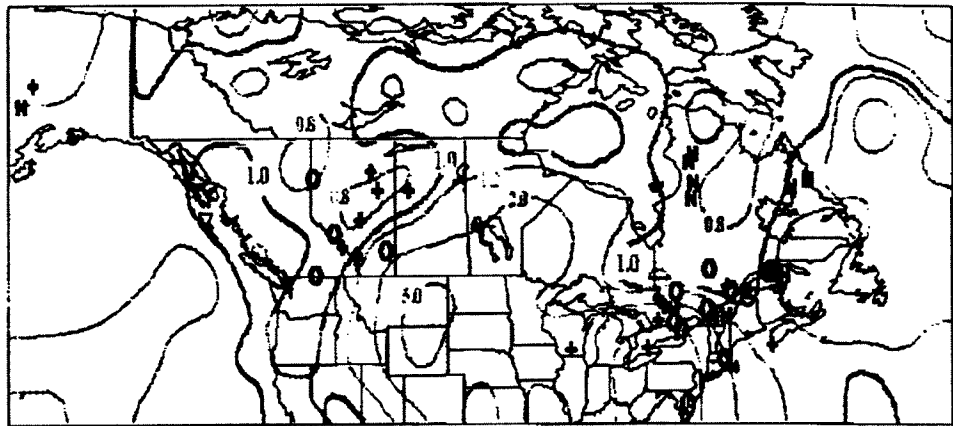


Figure 6. Charcoal anomalies superimposed over the mean FWI Ratio (2xCO₂/1xCO₂). Anomaly symbols as in Figure 5.

In summary, if the climate changes as suggested by the Canadian GCM we would anticipate large spatial variations in the fire weather and consequently, fire activity. Changes, increases and decreases in fire activity will impact the vegetation in a complicated fashion, accelerating vegetational change where fire increases and retarding vegetational change where fire decreases. The 6ky B.P. fire weather may be a reasonable analogue of a warmer climate to come, however, these results suggest even a more pronounced change in fire weather with greenhouse warming.

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