Journal of Vegetation Science 9: 469-476, 1998
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Future wildfire in circumboreal forests in relation to global warming

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Abstract. Despite increasing temperatures since the end of the Little Ice Age (ca. 1850), wildfire frequency has decreased as shown in many field studies from North America and Europe. We believe that global warming since 1850 may have triggered decreases in fire frequency in some regions and future warming may even lead to further decreases in fire frequency. Simulations of present and future fire regimes, using daily outputs from the General Circulation Model (GCM), were in good agreement with recent trends observed in fire history studies. Daily data, rather than monthly data, were used because the weather and, consequently, fire behavior can change dramatically over time periods much shorter than a month. The simulation and fire history results suggest that the impact of global warming on northern forests through forest fires may not be disastrous and that, contrary to the expectation of an overall increase in forest fires, there may be large regions of the Northern Hemisphere with a reduced fire frequency.

Keywords: Boreal forest; Climate model; Fire history; Global change.

Introduction

One perception of the impact of global warming is that circumboreal forests will be irreversibly damaged by uncontrollable wildfires. It is true that wildfire and climate are intimately linked (Swetnam 1993) and that throughout the past the fire regime has responded to changes in the climate. According to simulations with various general circulation models (GCMs), the earth's climate will be several degrees warmer by the end of the next century due to increasing atmospheric concentrations of radiatively active gases such as water vapor, carbon dioxide, methane, nitrous oxide and chlorofluorcarbons. A change in the fire regime in response to climatic warming could have a greater impact on forest dynamics than the direct effects of climatic warming for forests such as the circumboreal forests, where fire is the major disturbance (Payette 1992). Based on GCM results, increases in the frequency of forest disturbances, including fire, have been postulated. Such increases may cause changes in forest composition and may accelerate the rate of response of forest vegetation (Overpeck et al. 1990).

In order to understand how global warming may affect the areal extent and intensity of wildfires we can verify how wildfires responded to warming in the past and use this as an analogue for future changes. The mean temperature of the Northern Hemisphere during summer – the fire season – and through the year has risen since the end of the Little Ice Age, ca. 1850 (Boden et al. 1990). However, in Sweden, temperatures have returned to 1860 values after having increased from 1860 to 1940 (Alexandersson & Eriksson 1989). The signal of warming is much clearer in Canada where temperatures have increased since 1890, regionally at a rate of 1.7 °C per century (statistically significant at the 95% level for most of Canada; Gullett & Skinner 1992). During this period, fire frequency has decreased, as documented for many cases (Table 1). Some of these decreases might be a result of fire suppression activities, although some of these study regions have not been influenced by human activities. These empirical results are not in agreement with models that suggest universal increases in fire frequency with climatic warming (Overpeck et al. 1990; Anon. 1996). This disagreement is because an individual fire is a result of the complex set of interactions that include ignition agents, fuel conditions, topography and weather including temperature, relative humidity, wind velocity and the amount and frequency of precipitation. Increasing temperature alone does not necessarily mean a larger fire disturbance.

Our hypothesis is that the recent warming is an analogue of future warming and that future wildfires may respond in a manner similar to recent fire history. To test this we model the present and future fire regime using GCM outputs and compare it with recent trends in fire frequency observed in fire history studies during this period of warming since the middle 1800s. This study on northern forests is particularly important in that climate change is likely to have its greatest impact on boreal forests (Anon. 1996), and the boreal forests will be one of the first areas where climate change and its impacts are detectable. Transient conditions that would occur between present and future simulations were not addressed in this study. Many caveats accompany the use of GCMs. The resolution is coarse, paramaterization of land surfaces needs improvement and aerosols need to be incorporated in the models. Still, GCMs provide the best means available to estimate the impact of changes in the future climate on the fire regime at larger scales.

Material and Methods

To model the fire regimes we will use an established Fire Danger System. The Canadian Fire Danger System uses temperature, relative humidity, wind speed and precipitation to calculate a Fire Weather Index (FWI), which represents the intensity of a spreading fire. In this study we shall also use the Canadian General Circulation Model (GCM) to model the present and future fire regimes to evaluate the effect of climate change on fire regimes. The Canadian GCM is a coupled atmosphere - ocean model with a transform grid spacing of 3.75° by 3.75° and full diurnal and annual cycles (Boer et al. 1992; McFarlane et al. 1992). Daily rather than monthly data were used because the weather and, consequently, fire behavior can change dramatically over time periods much shorter than a month. Temperature, specific humidity, precipitation and wind speed were obtained every 12 h (0000 and 1200 GMT) for 9 yr for both the $1 \times CO_2$ and $2 \times CO_2$ simulations. The $1 \times CO_2$ simulation uses 330 ppm of CO_2 and approximates the 1960-80 period whereas the $2 \times CO_2$ simulation uses 660 ppm and might represent conditions found at the end of the next century. We used the maximum daily temperature, relative humidity derived from the specific humidity, 24-h precipitation and the 12-h (12-00 GMT) mean wind speed to calculate components of the Canadian Fire Weather Index (FWI) System during the fire season (Van Wagner 1987). We defined the fire season as 1 April to 30 September in North America and 1 May to 31 August in northern Europe. The intensity of spreading fire (Fire Weather Index) was calculated for both simulations and then compared by taking the ratio of $2 \times CO_2$ to $1 \times CO_2$. Extreme FWI maximums in addition to the mean values for the 9 yr were used in this analysis. Extremes were used because only a few days with extreme fire weather conditions are responsible for most of the area burned by forest fires (Flannigan & Harrington 1988).

A literature survey of relevant empirical fire history studies is presented in Table 1. The results have been presented without interpretation. Given the variation in methods employed to gather the observed fire histories, it was not practical to re-analyse the data.

Results

Fire history studies

Table 1 summarizes information from fire history studies for North America and northern Europe along with the projected change in FWI. All empirical studies have shown either a decrease or no change in fire frequency during the 20th century. In the southern Canadian Rocky Mountains a decrease in fire frequency, which started ca. 1750, was attributed to a moister climate associated with the Little Ice Age. A study on Kootenay reported on a subsequent and more important decrease ca. 1930, which was attributed to an increase in precipitation (Masters 1990). These changes in fire frequency did not coincide with the recent warming since the end of the Little Ice Age because changes in the precipitation regime were not synchronous with the temperature changes. The precipitation regime seems to be the dominant factor influencing fire frequency.

There is general agreement between the fire history data and the simulated changes in fire regime. While empirical results agree with simulations for the southern Rocky Mountains, results from Jasper, West-central Alberta, northwestern Ontario and subarctic Québec are contradictory, depending on whether we consider the mean or maximum FWI. In most cases the observed decreases in fire frequency were previously attributed to fire suppression, although according to our results climate change may also have played an important role. Observed decreases at Wood Buffalo, Rutledge Lake, Algonquin Park, western and central Québec and Vermont agree with the simulations and are thus very likely to be climatically driven. Since effective fire suppression started early in Vermont and Algonquin Park, it may have contributed to enhance the decrease. However, the decrease observed in northwestern Quebec appears only climatically driven as effective fire suppression is a recent occurrence (Bergeron 1991). Conversely, the decrease in fire frequency observed in Itasca and Boundary Waters contrast with an important increase in simulated mean and maximum FWI. Fire frequency would have increased dramatically in Minnesota in the 20th century in the absence of fire suppression (Clark 1988). The same may be true for New Brunswick and Nova Scotia where, despite an increased fire frequency, the average area burned has remained the same.

For the study sites in northern Europe there are clear indications for a decrease in fire frequency. Generally, the situation here is more complicated because of the more pronounced human influence. Fire frequencies were higher in the 1800s partly due to the slash-and-burn practice, i.e. clearance of the forest for agricultural purposes (Vasari 1965; Bradshaw & Hannon 1992; Bradshaw 1993). Additionally, during the 1900s fires were to some extent suppressed; this would reduce fire frequency. On the other hand, the fire regime changed almost simultaneously at most sites; this would suggest that climatic control on fire frequency is more important than human impact. The simulation results support the conclusion that the northern study sites show a decrease in fire frequency. The increases in fire frequency simulated for the southern study sites do not match reality, probably because of changes in land use pattern and the fire exclusion policy.

GCM Simulations

The mean FWI values derived from the $1 \times CO_2$ scenario were compared against the mean values calculated from observations for 29 stations across Canada and 11 Swedish stations (Harrington et al. 1983). The mean values obtained from the $1 \times CO_2$ simulation were reasonably well correlated with the observed mean FWI values (r = 0.66 for Canada and 0.70 for Sweden) and we feel that the FWI values from the simulation are a reasonable approximation of the recent past. Fig. 1 shows the ratio of the $2 \times CO_2$ to $1 \times CO_2$ values for both mean FWI and maximum FWI for the 9 yr of simulation for North America and Europe. There is a great deal of regional variation between areas where FWI decreases in a $2 \times CO_2$ scenario (values below 1.00) to areas where FWI has increased greatly in the warmer climate. Much of eastern Canada and western Canada have ratios below 1.00, indicating that FWI has decreased despite the warmer temperatures associated with a $2 \times CO_2$ climate. Significant increases in FWI are evident for parts of central North America. The ratio of extreme maximum values of the FWI for the 9-yr period shows a similar pattern, with higher ratios over central continental areas and lower values over portions of eastern Canada. On the other hand, there are increases in the maximum FWI over portions of western Canada. For northern Europe, Fig. 1 shows increased mean FWI values over the southern half of Sweden and extreme southeastern Finland for warmer conditions whereas the remainder of northern Europe shows decreased mean FWI values. Results for maximum FWI values show a similar pattern as compared with mean FWI, with the exception of southern Norway where FWI increased.

Table 1. Historical fire frequency studies in relation to simulated values for the Fire Weather Index (FWI) for North America and Northern Europe. Long. = Longitude (°W in N. America; °E in N. Europe); FWI mean and max. values are as % change. Trend = driection of change: ↓ = decrease; ≈ no change. Ref. = No. of reference used with details on local situation.

Location	Long.	Lat.	FWI mean	FWI max	Trend	Ref.
North America						
Jasper Park	118.1	52.9	100	– 20	↓	1
W. Central Alberta	117.8	53.4	– 30	60	↓	2
Glacier Park	117.6	51.3	0	– 20	≈	3
Yoho Park	116.5	51.4	0	– 22	≈	4
Kootenay	115.8	50.5	– 22	0	↓	5
Kananaskis	115.4	50.8	0	– 25	≈	6
Wood Buffalo Park	113.0	59.0	– 10	0	↓	7
Rutledge Lake	110.5	61.7	10	– 20	↓	8
Itasca State Park	95.2	47.2	100	50	↓	9
Northwestern Ontario	92.0	51.5	100	– 10	↓	10
Boundary Waters	91.5	48.0	50	100	↓	11
Algonquin Park	77.9	45.9	– 30	– 30	↓	12
Western Quebec	79.3	48.5	– 28	– 30	↓	13
Subarctic Quebec	75.0	57.0	10	– 25	≈	14
Central Quebec	74.0	48.0	– 10	– 10	↓	15
Vermont	73.5	44.2	-5	– 10	↓	16
New Brunswick	67.0	47.0	20	50	≈	18
Northern Europe						
Älvaden	13.3	61.3	20	20	↓	19
Falun	15.3	60.4	40	30	↓	20
Fiby Forest	17.2	59.5	40	50	↓	21
Vindelälven Valley	19.0	64.5	0	0	↓	22
Vindeln	19.3	64.1	0	0	↓	23
Muddus Nat. Park	20.1	67.0	– 20	– 20	↓	24
Nattavaara	20.3	66.5	– 20	– 20	↓	25
Gällivare	20.4	67.1	– 20	– 20	↓	20
Harads	21.0	66.1	– 20	– 20	↓	26
Lake Ahvenainen	25.0	62.0	– 10	20	↓	27
Kuusamo	28.0	65.5	– 10	0	↓	28
Ulvinsalo	30.2	63.5	0	0	↓	29

1. No major fires since 1889 and very few since 1908 (Tande 1979).
2. Fire frequency decreased since 1915 (Van Wagner 1978).
3. Frequency decreased since ca. 1760 from a 80-yr to a 110-yr cycle (Johnson et al. 1990).
4. Frequency decreased from a 50-yr cycle prior to 1740 to a 150-yr cycle after 1740 (Johnson & Wowchuk 1993).
5. Frequency decreased ca. 1788 from a 60-yr to a 130-yr cycle. Another change occurred ca. 1928; the fire cycle is now > 2700 yr (Masters 1990).
6. Frequency decreased from a 50-yr fire cycle prior to 1730 to a 90-yr cycle after 1730 (Johnson & Larsen 1991).
7. Frequency decreased ca. 1860 from a 38-yr fire to a 63-yr cycle (Larsen 1994).
8. Frequency decreased ca. 1780; a more drastic decrease occurred early this century (Johnson 1979; Johnson 1992).
9. Frequency decreased since 1600; since 1910 frequency very low (Clark 1990).
10. Frequency decreased ca.1925 (Suffling et al. 1982).
11. No major fires observed since 1894; number of (minor) fires decreased since 1910 (Heinselman 1973).
12. No large fires observed since 1870 (Cwynar 1977).
13 Frequency decreased ca. 1870 from a 74-yr to a > 112-yr cycle (Bergeron 1991).
14. Number of fires increased since 1900, total area burned did not change – individual fires were smaller on average (Payette et al. 1989).
15. Present forest originated largely after fire events > 100 yr ago (Cogbill 1985). 16. No fires observed since 1851 (Mann et al. 1994).
17. Similar to 14 (Wein & Moore 1977).
18. Number of fires increased but fire size and average area burned decreased (Wein & Moore 1979).
19. Significant decrease in fire frequency since 1850 (Kohh 1975).
20. Total area burned decreased – official statistics 1888-1934 (Kinnman 1936).
21. Lower frequency since ca, 1800 (Bradshaw & Hannon 1992; Bradshaw 1993).
22. Cycle changed from 100-yr to 3500-yr ca. 1880 (Zackrisson 1977).
23. Study period 1510-1930. No fires after 1887 (Tiren 1937).
24. Frequency decreased since ca. 1870 (Engelmark 1984; 1987).
25. Cycle increased from 187-yr prior to 1870 to 371-yr after 1870 (Engelmark et al. 1994).
26. Study period 1081 to present. No fires since 1888 (Zackrisson 1981).
27. Lower frequency since the mid-1800s (Tolonen 1983).
28. Lower frequency since the late 1800s (Vasari 1965).
29. Significant decrease in frequency since late 1800s (Haapanen & Siitonen 1978).

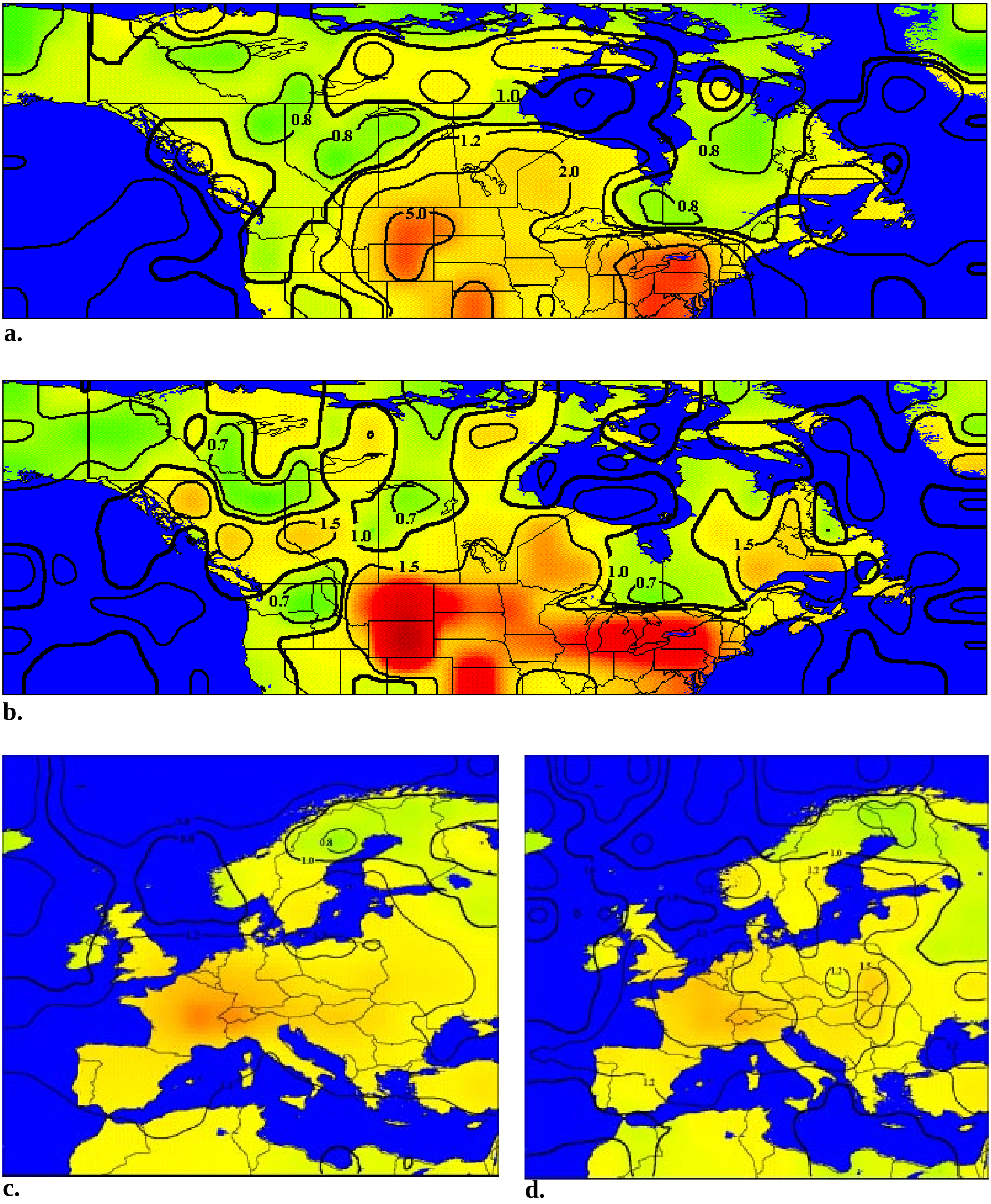

Fig. 1. Mean and Maximum FWI Ratios (2×CO_2/1×CO_2)for North America (**a**,**b**) and Europe (**c**,**d**).

Fig. 2 shows an increase in summer temperature by 2 - 6 °C for North America and Europe. An increase in temperature alone would lead to a higher FWI and hence a more severe fire regime; however, this is true only if all the other variables remain unchanged. FWI is sensitive to relative humidity, wind speed and precipitation as well. Fig. 2 also shows the ratio of the $2 \times CO_2$ precipitation to the $1 \times CO_2$ precipitation for the fire

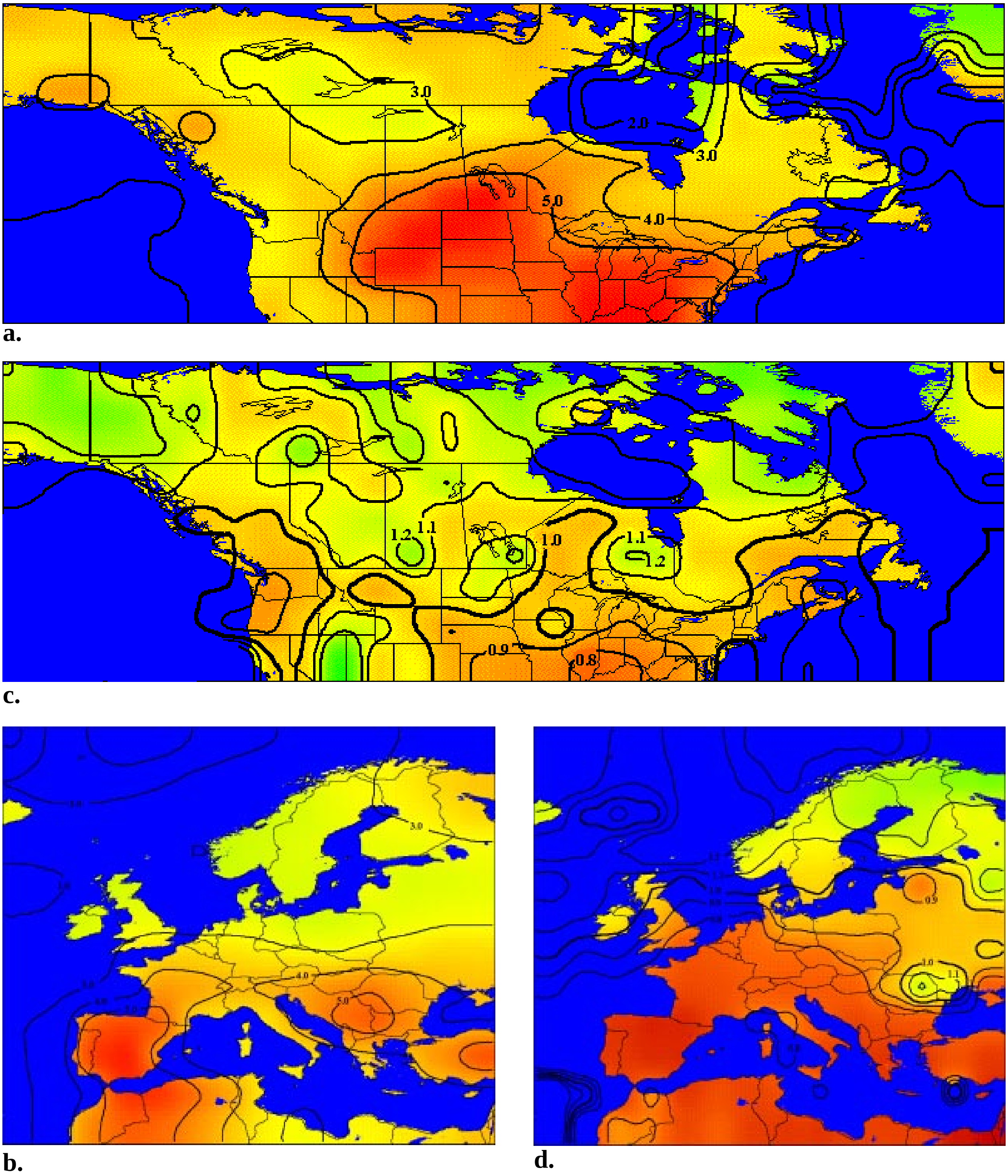

Fig. 2. Mean Temperature Change ($2{\times}CO_2$-$1{\times}CO_2$) for (**a**) North America and (**b**) Europe. Precipitation Ratio ($2xCO_2/1xCO_2$) for (**c**) North America and (**d**) Europe.

season. Precipitation amounts, which are higher for some of the regions for the $2 \times CO_2$ simulation as compared to the $1 \times CO_2$, can more than compensate for any increases in FWI due to increased temperature.

Additionally, there are regions where the relative humidity has increased in the warmer climate, which will also contribute to a decrease in FWI.

Discussion

The link between fire activity and climate is clear. For example, Swetnam (1993) studying the fire history of giant sequoia groves found that regionally synchronous fire occurrence was related to climate. In the boreal forest, Bergeron & Archambault (1993) using a 300-yr fire history from the Lake Duparquet area (48° 28' N, 79° 17' W), found an important decrease in the number and extent of fires starting ca. 100 yr ago. This period of decreasing fire frequency coincides with a reduced frequency of drought. In northern Sweden, Engelmark et al. (1994) showed that fire frequency decreased significantly from 1870 onwards over an area of ca. 3500 km^2 covering Muddus National Park and surroundings (66° 55' N, 20° 03' E). This 1870 break point coincides with the warming that began at the end of the Little Ice Age. Thus, changes in climate have a direct impact on fire activity. In these last two studies there is no indication that the natural fire regime was significantly influenced by man (Bergeron 1991; Engelmark et al. 1994).

Our results differ from those obtained from another study that found an increase in seasonal fire severity rating (a derivative of FWI) across Canada (Flannigan & Van Wagner 1991). 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. Our results are more consistent with recent fire history than the results from the three GCM studies. We believe that our results are more accurate because we are using daily data even though we are using only one GCM. Recently, Stocks et al. (1998) used monthly data from four GCMs (including the Canadian GCM) to examine climate change and forest fire potential in Russian and Canadian boreal forests. Their results show the same general trend in the monthly severity rating across Canada and are similar to our results.

If the disturbance regime changes as our results suggest then this could have a significant impact on the global carbon budget. In regions where fire increases the forest age class distribution will include younger stands and the historical role of the northern forest as a carbon sink will be reduced (Kurz & Apps 1993). However, in those regions where fire frequency decreases, the landscape will be composed of older stands, which will allow the boreal forest to continue as a carbon sink.

Climatic warming in North America would allow many species to extend their ranges northward (Solomon 1986; Liu 1990). Changing fire frequencies may hasten or retard this movement and may determine what species will be favored in the new disturbance regime (Suffling 1995).

It is difficult to generalize the influence of a changing fire regime on vegetation composition and the rate of vegetation change. It depends on the present vegetation complement and the suite of migratory species available and their interactions. Studies from Europe and North America have suggested that increased fire frequency accelerates vegetation change (Green 1982; Landhausser & Wein 1993). Increased fire frequency over the southern boreal forest in central Canada (as simulated) would probably hasten vegetation change from the present mixed-wood forest of aspen, poplar, birch, spruce and pine to an aspen/grassland mosaic presently bordering this forest. However, a decreased fire frequency over the southeastern boreal forest would result in some changes in the abundance of current species but would probably retard the movement of many species found in the Great Lakes-St. Lawrence Forest, which lies just south of the southeastern boreal forest. In particular, shade-tolerant *Abies balsamea* would increase in abundance if fire frequency is reduced. This decreasing fire frequency would increase the resistance to change and would result in a low invasion rate of southern species better adapted to the new climate. However, decreases in fire frequency might partially be compensated by increases in pest outbreaks (Fleming 1996). Research on interactions between climate, disturbance and vegetation are required in order to estimate the future composition and structure of the natural forest. These interactions could result in a highly altered forest ecosystem, which might represent new assemblages that do not have past analogues (Martin 1993).

Two aspects of the regional variation in FWI are striking. First, there is a dramatic increase in FWI with climatic change over central North America. Significant increases in FWI are suggested for the lower Great Lakes and for the Dakotas, Montana and Wyoming. Second, there are sizeable areas of North America and northern Europe where FWI has decreased. Noteworthy is the area of reduced FWI over western and northwestern sections of Canada where, historically, large portions of the landscape have been burned. Another aspect is that, according to our simulations, fire danger will decrease in the northern sections of northern Europe where traditionally forest fires have been large and frequent, while fire danger will increase over southern Sweden where forest fires are usually not severe. Consequences of climate change on fire disturbance must be viewed in a spatially dependent context.

Other factors such as ignition agents, length of the fire season and fire management policies may greatly influence the impact of climate change on the fire regime. Ignition probabilities may increase in a warmer world due to increased cloud-to-ground lightning discharges with warming (Price & Rind 1994). The fire season will start earlier in the spring and extend longer into the autumn, yielding a longer fire season (Wotton & Flannigan 1993). Fire management policies and effectiveness will continue to change. These are all confounding effects that may dampen or amplify the impact of a changing climate on the fire regime.

Our hypothesis that recent warming is an analogue for future warming has not been formally tested; however, our results suggest that the influence of increasing temperatures on fire frequency is expected to behave in a similar manner to that which has been observed during the warming of the last 150 yr. In fact, some of the warming observed over the last century is likely a result of human activities (Anon. 1996). Although the future warming will occur more rapidly than what has been experienced in the past century or the last 10 000 yr. Lastly, the variability in the climate will probably increase during the next century (Gregory & Mitchell 1995; Gregory et al. 1997), which could have a significant impact on the fire regime. Once again, we feel that using daily data instead of monthly data from the GCM allows us to incorporate this variability into our fire modelling (Gregory & Mitchell 1995).

This research highlights the large regional variation in the response of the fire regime to climatic change; regions of reduced fire severity can be found even for regions where warming has occurred. These simulations are in general agreement with recent fire history studies that document a decrease in fire frequency despite increasing temperatures. Finally, in those areas of significant increases in fire disturbance the result may not be disastrous, at least from an ecological viewpoint, even at locations where the vegetation may change from forest to grassland. After all, such changes have occurred naturally in the past (Ritchie 1983).

References

Anon. 1996. *Climate Change 1995 Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses.* Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge.

Alexandersson, H. & Eriksson, B. 1989. *Climate fluctuations in Sweden 1860-1987.* SMHI Reports Nr 58, Norrköping.

Bergeron, Y. 1991. The influence of island and mainland lakeshore landscapes on boreal forest fire regimes. *Ecology* 72: 1980-1992.

Bergeron, Y. & Archambault, S. 1993. Decreasing frequency of forest fires in the southern boreal zone of Québec and its relation to global warming since the end of the 'Little Ice Age'. *The Holocene* 3: 255-259.

Boden, T.A., Kanciruk, P. & Farrell, M.P. 1990. *Trends '90: A compendium of data on global change.* ORNL/CDIAC-36. Department of Energy, Washington, DC.

Boer, G.J., McFarlane, N.A. & Lazare, M. 1992. Greenhouse gas-induced climate change simulated with the CCC second-generation General Circulation Model. *J. Clim.* 5: 1045-1077.

Bradshaw, R.H.W. 1993. Tree species dynamics and disturbance in three Swedish boreal forest stands during the last two thousand years. *J. Veg. Sci.* 4: 759-764.

Bradshaw, R.H.W. & Hannon, G.E. 1992. Climatic change, human influence and disturbance regime in the control of vegetation dynamics within Fiby forest, Sweden. *J. Ecol.* 80: 625-632.

Clark, J.S. 1988. Effect of climate change on fire regimes in northwestern Minnesota. *Nature* 334: 233-235.

Clark, J.S. 1990. Fire and climate change during the last 750 years in northwestern Minnesota. *Ecol. Monogr.* 60: 135-159.

Cogbill, C.V. 1985. Dynamics of the boreal forests of the Laurentian Highlands, Canada. *Can. J. For. Res.* 15: 252-261.

Cwynar, L.C. 1977. Recent history of fire of Barron Township, Algonquin Park. *Can. J. Bot.* 55: 1524-1538.

Engelmark, O. 1984. Forest fires in the Muddus National Park during the past 600 years. *Can. J. Bot.* 62: 893-898.

Engelmark, O. 1987. Fire history correlations to forest type and topography in northern Sweden. *Ann. Bot. Fenn.* 24: 317-324.

Engelmark, O., Kullman, L. & Bergeron, Y. 1994. Fire and age structure of Scots pine and Norway spruce in northern Sweden during the past 700 years. *New Phytol.* 126: 163-168.

Flannigan, M.D. & Harrington, J.B. 1988. A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada 1953-80. *J. Appl. Meteorol.* 27: 441-452.

Flannigan, M.D. & Van Wagner, C.E. 1991. Climate change and wildfire in Canada. *Can. J. For. Res.* 21: 66-72.

Fleming, R.A. 1996. A mechanistic perspective of possible influences of climate change on defoliating insects in North America's boreal forests. *Silva Fenn.* 30: 281-294.

Green, D.G. 1982. Fire and stability in the post-glacial forests of southwest Nova Scotia. *J. Biogeogr.* 9: 29-40.

Gregory, J.M. & Mitchell, J.F.B. 1995. Simulation of daily variability of surface temperature and precipitation over Europe in the current and $2xCO_2$ climates using the UKMO climate model. *Q. J. R. Meteorol. Soc.* 121: 1451-1476.

Gregory, J.M., Mitchell, J.F.B. & Brady, J. 1997. Summer drought in northern midlatitudes in a time-dependent CO_2 climate experiment. *J. Clim.* 10: 662-686.

Gullett, D.W. & Skinner, W.R. 1992. The state of Canada's climate: Temperature change in Canada 1895-1991. SOE Report 92-2 Environ. Can., Ottawa.

Haapanen, A & Siitonen, P. 1978. Forest fires in Ulvinsalo strict nature reserve. *Silva Fenn,* 12: 187-200.

Harrington, J.B., Flannigan, M.D. & Van Wagner, C.E. 1983. A study of the relation of components of the Fire Weather Index to monthly provincial area burned by wildfire in Canada 1953-80. Inf. Rep. PI-X-25, Canadian Forest Service, Chalk River, Ont.

Heinselman, M.L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. *Quat. Res.* 3: 329-382.

Johnson, E.A. 1979. Fire recurrence in the subarctic and its implications for vegetation composition. *Can. J. Bot.* 57: 1373-1379.

Johnson, E.A. 1992. *Fire and vegetation dynamics: studies from the North American boreal forests* Cambridge University Press, Cambridge.

Johnson, E.A. & Larsen, C.P.S. 1991. Climatically induced change in fire frequency in the southern Canadian Rockies. *Ecology* 72: 194-201.

Johnson, E.A. & Wowchuk, D.R. 1993. Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies. *Can. J. For. Res.* 23: 213-1222.

Johnson, E.A., Fryer, G.I. & Heathcott, M.J. 1990. The influence of man and climate on frequency of fire in the interior wet belt forest, British Columbia. *J. Ecol.* 78: 403-412.

Kinnman, G. 1936. Skogseldsrisken och väderleken. *Sver. Skogsvårdsförb. Tidskr.* 34: 481-512.

Kohh, E. 1975. A study of fires and hard pan in the forests of Älvdalen. *Sver. Skogsvårdsförb. Tidskr.* 73: 299-336.

Kurz, W.A. & Apps, M.J. 1993. Contribution of northern forests to the global C cycle: Canada as a case study. *Water Air Soil Pollut.* 70: 163-176.

Landhausser, S.M. & Wein, R.W. 1993. Postfire vegetation recovery and tree establishment at the Arctic treeline: climate-change vegetation-response hypotheses. *J. Ecol.* 81: 665-672.

Larsen, C.P.S. 1994. Spatial and temporal variations in fire frequency in the boreal forest of northern Alberta. Ph.D. Thesis, McMaster University, Hamilton.

Liu, K.-B. 1990. Holocene paleoecology of the Boreal Forest and the Great Lakes - St Lawrence Forest in northern Ontario. *Ecol. Monogr.* 60: 179-212.

Mann, D.H., Engstrom, F.B. & Bubier, J.J. 1994. Fire history and tree recruitment in an uncut New England forest. *Quat. Res.* 42: 206-215.

Martin, P. 1993. Vegetation responses and feedbacks to climate: a review of models and processes. *Clim. Dyn.* 8: 201-210.

Masters, A.M. 1990. Changes in fire frequency in Kootenay National Park, Canadian Rockies. *Can. J. Bot.* 68: 1763-1767.

McFarlane, N.A., Boer, G.J., Blanchet, J.-P. & Lazare, M. 1992. The Canadian Climate Centre second-generation General Circulation Model and its equilibrium climate. *J. Climatol.* 5: 1013-1044.

Overpeck, J.T., Rind, D. & Goldberg, R. 1990. Climate-induced changes in forest disturbance and vegetation. *Nature* 343: 51-53.

Payette, S. 1992. Fire as a controlling process in the North American boreal forest. In: Shugart, H., Leemans, R. & Bonan, G.B. (eds.) *A systems analysis of the global boreal forest*, pp. 144-169. Cambridge University Press, Cambridge.

Payette, S., Morneau, C., Sirois, L. & Desponts, M. 1989. Recent fire history of the Northern Quebec biomes. *Ecology* 70: 656-673.

Price, C. & Rind, D. 1994. The impact of a 2xCO_2 Climate on lightning-caused fires. *J. Climatol.* 7: 1484-1494.

Ritchie, J.C. 1983. The Paleoecology of the central and northern parts of the glacial Lake Agassiz basin. *Geol. Assoc. Can. Spec. Pap. No. 26*: 157-170.

Solomon, A.M. 1986. Transient response of forests to CO_2 induced climate change: Simulation modeling experiments in eastern North America. *Oecologia* (*Berl.*) 68: 567-579.

Stocks, B.J., Fosberg, M.A., Lynham, T.J., Mearns, L., Wotton, B.M., Yang, Q. Jin, J.-Z., Lawrence, K., Hartley, G.R., Mason, J.A. & McKenney, D.W. 1998. Climate change and forest fire potential in Russian and Canadian boreal forests. *Clim. Change* 38: 1-13.

Suffling, R. 1995. Can disturbance determine vegetation distribution during climate warming. A boreal test. *J. Biogeogr.* 22: 501-508.

Suffling, R. Smith, B. & Dal Molin, J. 1982. Estimating past forest age distributions and disturbance rates in North-Western Ontario: a demographic approach. *J. Environ. Manage.* 14: 45-56.

Swetnam, T.W. 1993. Fire history and climate change in giant Sequoia groves. *Science* 262: 885-889.

Tande, G.F. 1979. Fire history and vegetation pattern of coniferous forests in Jasper National Park, Alberta. *Can. J. Bot.* 57: 1912-1931.

Tiren, L. 1937. Forestry historical studies in the Degerfors District of the province of Västerbotten. *Medd. Stat. Skogsforskn. Inst.* 30: 67-322.

Tolonen, K. 1983. The post-glacial fire record. In: Wein, R.W. & MacLean, D.A. (eds.) *The role of fire in northern circumpolar ecosystems. SCOPE 18,* pp. 21-44. New York, NY.

Van Wagner, C.E. 1978. Age-class distribution and the forest fire cycle. *Can. J. For. Res.* 8: 220-227.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. *For. Tech. Rep. 35* Can. For. Serv., Ottawa.

Vasari, Y. 1965. Studies on the vegetational history of the Kuusamo district (North East Finland) during the late-quaternary period. IV. The age and origin of some present-day vegetation types. *Ann. Bot. Fenn.* 2: 248-273.

Wein, R.W. & Moore, J.M. 1977. Fire history and rotations in the New Brunswick Acadian Forest. *Can. J. For. Res.* 7: 285-294.

Wein, R.W. & Moore, J.M. 1979. Fire history and recent fire rotation periods in the Nova Scotia Acadian forest. *Can. J. For. Res.* 9: 166-178.

Wotton, B.M. & Flannigan, M.D. 1993. Length of the fire season in a changing climate *For. Chron.* 69: 187-192.

Zackrisson, O. 1977. Influence of forest fires on the north Sweden boreal forest. *Oikos* 29: 22-32.

Zackrisson, O. 1981. *Naturresursutnyttjande i relation till skogsekosystemens tidigare dynamik och struktur i Lule älvdal*. Report Luleälvsprojektet, Umeå University, Umeå.

Received 27 December 1996;
Revision received 7 November 1997;
Accepted 29 April 1998.