CLIMATE CHANGE AND FOREST FIRE POTENTIAL IN RUSSIAN AND CANADIAN BOREAL FORESTS

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Abstract. In this study outputs from four current General Circulation Models (GCMs) were used to project forest fire danger levels in Canada and Russia under a warmer climate. Temperature and precipitation anomalies between $1 \times CO_2$ and $2 \times CO_2$ runs were combined with baseline observed weather data for both countries for the 1980–1989 period. Forecast seasonal fire weather severity was similar for the four GCMs, indicating large increases in the areal extent of extreme fire danger in both countries under a $2 \times CO_2$ climate scenario. A monthly analysis, using the Canadian GCM, showed an earlier start to the fire season, and significant increases in the area experiencing high to extreme fire danger in both Canada and Russia, particularly during June and July. Climate change as forecast has serious implications for forest fire management in both countries. More severe fire weather, coupled with continued economic constraints and downsizing, mean more fire activity in the future is a virtual certainty. The likely response will be a restructuring of protection priorities to support more intensive protection of smaller, high-value areas, and a return to natural fire regimes over larger areas of both Canada and Russia, with resultant significant impacts on the carbon budget.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has recently concluded (IPCC, 1995) that 'the observed increase in global mean temperature over the last century (0.3–0.6 °C) is unlikely to be entirely due to natural causes, and that a pattern of climate response to human activities is identifiable in the climatological record'. There is also evidence of an emerging pattern of climate response to forcings by greenhouse gases and sulphate aerosols, as evidenced by geographical, seasonal and vertical temperature patterns. In Canada and Russia this pattern of observed changes has taken the form of major winter and spring warming in west-central and northwestern Canada and virtually all of Siberia over the past three decades, resulting in temperature increases of 2–3 °C over this period (Environment Canada, 1995).

Numerous General Circulation Models (GCMs) project a global mean temperature increase of 0.8–3.5 °C by 2100 AD, a change much more rapid than any experienced in the past 10,000 years. Most significant temperature changes are projected at higher latitudes and over land. In addition, greatest warming is expected to occur in winter and spring, similar to the trends measured recently,

although warming is projected for all seasons. While GCM projections vary, in general winter temperatures are expected to rise 6–10 °C and summer temperatures 4–6 °C over much of Canada and Russia with a doubling of atmospheric carbon dioxide. Global precipitation forecasts under a $2 \times CO_2$ climate are more variable among GCMs, but indications are that large increases in evaporation over land due to rising air temperatures will more than offset minor increases in precipitation amounts. In addition, changes in the regional and temporal patterns and intensity of precipitation are expected, increasing the tendency for extreme droughts and floods.

Despite their coarse spatial and temporal resolution, GCMs provide the best means currently available to project future climate and forest fire danger on a broad scale. However, Regional Climate Models (RCMs) currently under development (e.g., Caya et al., 1995), with much higher resolution, will permit more accurate regional-scale climate projections. In recent years GCM outputs have been used to estimate the magnitude of future fire problems. Flannigan and Van Wagner (1991) used results from three early GCMs to compare seasonal fire weather severity under a $2 \times CO_2$ climate with historical climate records, and determined that fire danger would increase by nearly 50% across Canada with climate warming. Wotton and Flannigan (1993) used the Canadian GCM to predict that fire season length across Canada would increase by 30 days in a $2 \times CO_2$ climate. An increase in lightning frequency across the northern hemisphere is also expected under a doubled CO_2 scenario (Fosberg et al., 1990; Price and Rind, 1994). In a recent study (Fosberg et al., 1996) used the Canadian GCM, along with recent weather data, to evaluate the relative occurrence of extreme fire danger across Canada and Russia, and showed a significant increase in the geographical expanse of the worst fire danger conditions in both countries under a warming climate.

In this study, we use Canadian and Russian fire weather data from the 1980s, the warmest decade on record in Canada (Gullet and Skinner, 1992), in conjunction with outputs from four recent GCMs, to compare the spatial distribution of current seasonal levels of fire weather severity across both countries with those projected under a $2 \times CO_2$ climate. In addition, outputs from the Canadian GCM are used to track the monthly distribution of fire weather severity for both countries under current and 'future' conditions. These projections consider only the equilibrium climate once $2 \times CO_2$ conditions have been reached. A static analysis of this type, while informative, does not reflect the rate of change in fire climate and fire regimes as atmospheric greenhouse gas concentrations increase toward $2 \times CO_2$ levels. Transient analyses are required to address future fire impacts in the most realistic manner (Kurz and Apps, 1995).

2. Background

Climate warming of the magnitude projected can be expected to have major impacts on the forests of northern circumpolar countries. Based on GCM projections large-scale shifting of forest vegetation northward is expected (Solomon and Leemans, 1989; Rizzo and Wilken, 1992; Smith and Shugart, 1993), at rates much faster than previously experienced during earlier climate fluctuations. Increased forest fire activity is expected to be an early and significant result of a trend toward warmer and drier conditions (Stocks, 1993), accelerating the rate of vegetation shifting, and resulting in a decrease in biospheric carbon storage (Kasischke et al., 1995; Kurz and Apps, 1995; Shvidenko et al., 1996; Stocks et al., 1996). This would likely result in a positive feedback loop between fires in boreal ecosystems and climate change, with more carbon being released from boreal ecosystems than is being stored (Kurz et al., 1995a).

While fossil fuel burning contributes most significantly to increasing atmospheric greenhouse gas concentrations, emissions from biomass burning of the world's vegetation (forests, savannas, and agricultural lands) has recently been recognized as an additional major source of greenhouse gas emissions (Crutzen and Andreae, 1990). Recent cooperative international experiments (e.g., Andreae et al., 1994; FIRESCAN Science Team 1994) have confirmed that biomass burning produces up to 40% of gross carbon dioxide and 38% of tropospheric ozone, along with a suite of less common, but equally important greenhouse gases (Levine et al., 1995). While most biomass burning emissions originate from savanna and forest conversion burning in the tropics, there is a growing realization that boreal and temperate forest fire emissions are likely to play a much larger role under a warming climate. Cofer et al. (1996) recently outlined a number of reasons why the importance of atmospheric emissions from boreal fires may be underestimated: the tremendous fluctuations in annual area burned in the boreal zone, the fact that boreal fires are located at climatically sensitive northern latitudes, the potential for positive feedback between climate warming and boreal fire activity, and the high energy level of boreal fires which typically produce smoke columns reaching into the upper troposphere.

Forest fires have been a natural and dominant disturbance regime in global boreal forests for millennia, and recent statistics from Canada, Alaska, and Russia illustrate that, despite reasonably successful fire management strategies in these countries, forest fires still exert a significant influence on boreal ecosystem dynamics (Stocks, 1991; Kurz et al., 1995b). While intensive forest management has virtually eliminated large fires in Scandinavia, current estimates are that 5–10 million hectares burn annually in the circumpolar boreal zone (Stocks, 1991; Cahoon et al., 1994). Fire activity has been increasing over the past three decades in Canada, averaging 2.8 million hectares annually since 1980 (Stocks et al., 1996), but a lack of complete data prior to satellite coverage in the early 1970s precludes comparing this trend with fire statistics from earlier this century. Despite recent improve-

ments due to satellite monitoring, Russian fire statistics prior to the early 1990s are considered to have been vastly underestimated for political reasons. What is true, however, is that major forest fire years are highly episodic and are usually the result of short-term extreme fire weather situations in which numerous fires overwhelm fire management resources. In addition, Canadian, Alaskan, and Russian fire management agencies have always practiced a form of 'modified protection' in their more remote regions, gauging protection response in terms of values-at-risk. Under these policies boreal fires are effectively permitted to assume their natural role in these regions, contributing substantially to national area-burned figures. In addition, forest fire management agencies in these countries are facing severe and growing budget constraints at a time when protection costs are steadily rising. All of these factors combined suggest that boreal fire activity will escalate in the near future, underscoring the need to accurately project future boreal fire regimes.

3. Methods

Four current atmospheric GCMs were chosen for this study, as these models contain relatively simple to very complex coupling of the atmosphere, biosphere, and oceans, along with differing parameterizations of sub grid scale processes, and provide a robust range of climate predictions. These models are the Canadian Climate Centre GCM (Boer et al., 1992; McFarlane et al., 1992), the United Kingdom Hadley Centre GCM (Wilson and Mitchell, 1987), the Max Planck Institute for Meteorology (Germany) GCM (Cubasch et al., 1990), and the National Centre for Atmospheric Research (U.S.A.) GCM (Meehl et al., 1993).

Daily May–August weather data was collected for the 1980s for 224 Russian and 191 Canadian climate stations. Local noon measurements of temperature, relative humidity, windspeed and precipitation were used to calculate the component codes and indices of the Canadian Fire Weather (FWI) System (Van Wagner, 1987) for each station. Daily FWI values were then converted to Daily Severity Rating (DSR) values using a technique developed by Williams (1959) and modified by Van Wagner (1970). This severity rating technique permits the integration of fire severity over periods of various lengths, from daily (DSR) through monthly (MSR) to seasonal (SSR) values. In this analysis both MSR and SSR values are used. The FWI System provides an assessment of relative fire potential based solely on weather observations, and does not take forest type into consideration.

Average monthly temperature, relative humidity, windspeed, and precipitation anomalies (differences between the $1 \times CO_2$ control and $2 \times CO_2$ outputs) were determined for each model grid point for each of the four GCMs. Relative humidity and windspeed showed minimal change between the control and $2 \times CO_2$ runs, while significant anomalies were observed for both temperature and precipitation. The average monthly temperature anomaly for each grid point was then added to the observed daily temperature (from the 1980s data) at the nearest weather station,

while the monthly precipitation anomaly was factored in as a percentage (positive or negative) of each rainfall event that occurred during that month. This resulted in two datasets: the 1980s baseline observed data, and that dataset augmented with temperature and precipitation anomalies, which serves as a surrogate for the $2 \times CO_2$ climate. MSR and SSR outputs were then mapped for both scenarios using a Geographic Information System (GIS), and the areal distribution of fire danger levels determined.

Although fire danger classes cannot be determined when averaging monthly fire danger indicies, a study of fire weather climatology in Canada and Russia during the 1980s (Stocks and Lynham, 1996) produced frequency distributions of MSR values in both countries. Although there are strong regional differences, in general, MSR values <1, 1–2, 2–3, 3–4, 4–6, and >6 occur with frequencies of 40%, 28%, 14%, 7%, 7%, and 4% respectively. In general, MSR or SSR values above 7 represent extreme fire behavior potential, values between 3 and 7 represent high to very high potential, values between 1 and 3 constitute moderate fire potential, and values <1 equate to low fire potential.

4. Results and Discussion

MSR maps for the fire season months of May through August, based on the 1980s observed weather, are presented in Figure 1. In general, fire danger conditions are highest in west-central Canada and Siberia, the regions of both countries experiencing the most continental climate. The progression of fire danger from south to north with fire season development is evident in both Russia and Canada. Extreme fire danger is limited to the south-central regions of both countries in May, but expands to cover large portions of both countries, particularly Siberia and west-central Canada in June. This pattern continues in July, but by August fire danger in both countries is moderating, although east-central Siberia continues to experience high to extreme fire danger. This pattern continues in September (not shown) when low fire danger conditions prevail over much of Canada and Russia, the exceptions being the southern, unforested regions in both countries. From Figure 1 it is also obvious that an immense area of Siberia experiences extreme fire danger during the summer months, an area perhaps three times the size of the similarly-affected region in west-central Canada. In addition, a strong dichotomy in fire danger levels exists between eastern and western Canada, reflecting significantly different climate regimes.

SSR maps for the 1980s baseline data and the $2 \times CO_2$ scenarios for the four GCMs are shown in Figure 2. There is a strong similarity in the geographical pattern of fire severity for all models under a doubled CO_2 climate, indicating that some confidence can be placed on the predicted change. In general, all models show a significant increase in the area under high to extreme fire danger, particularly in central Canada and Siberia.
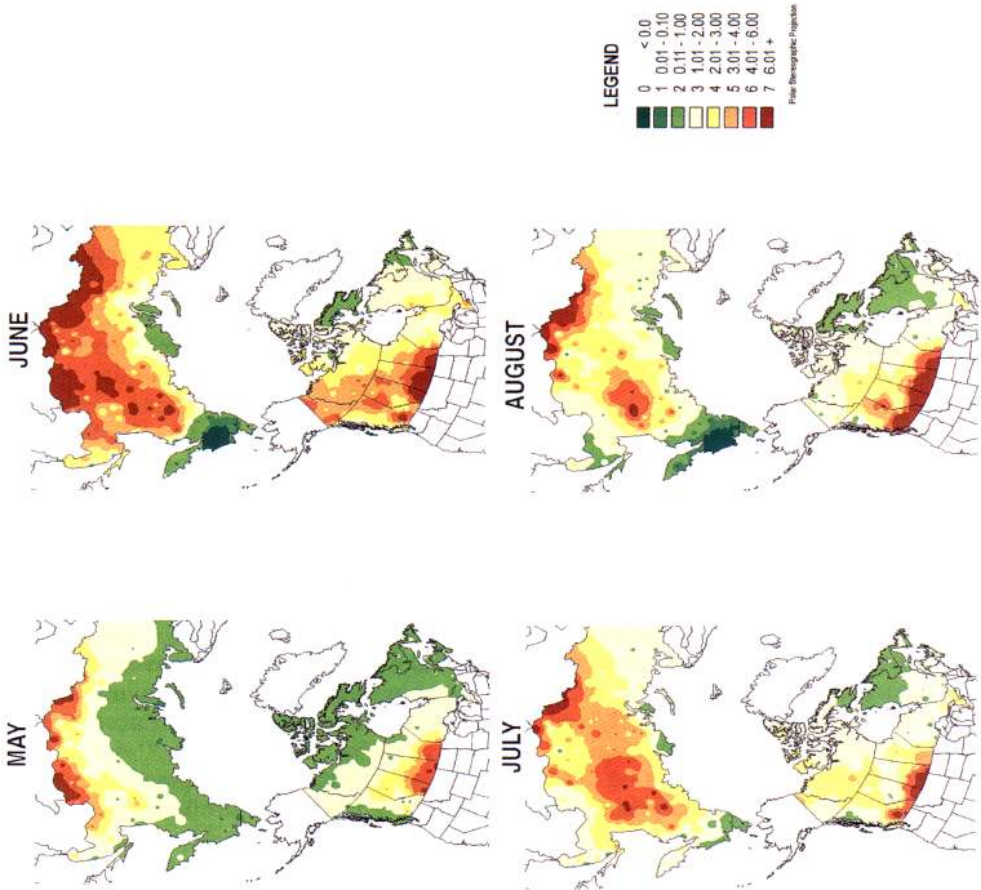
Figure 1. Average Monthly Severity Rating (MSR) maps for Canada and Russia, based on measured 1980–1989 daily weather.
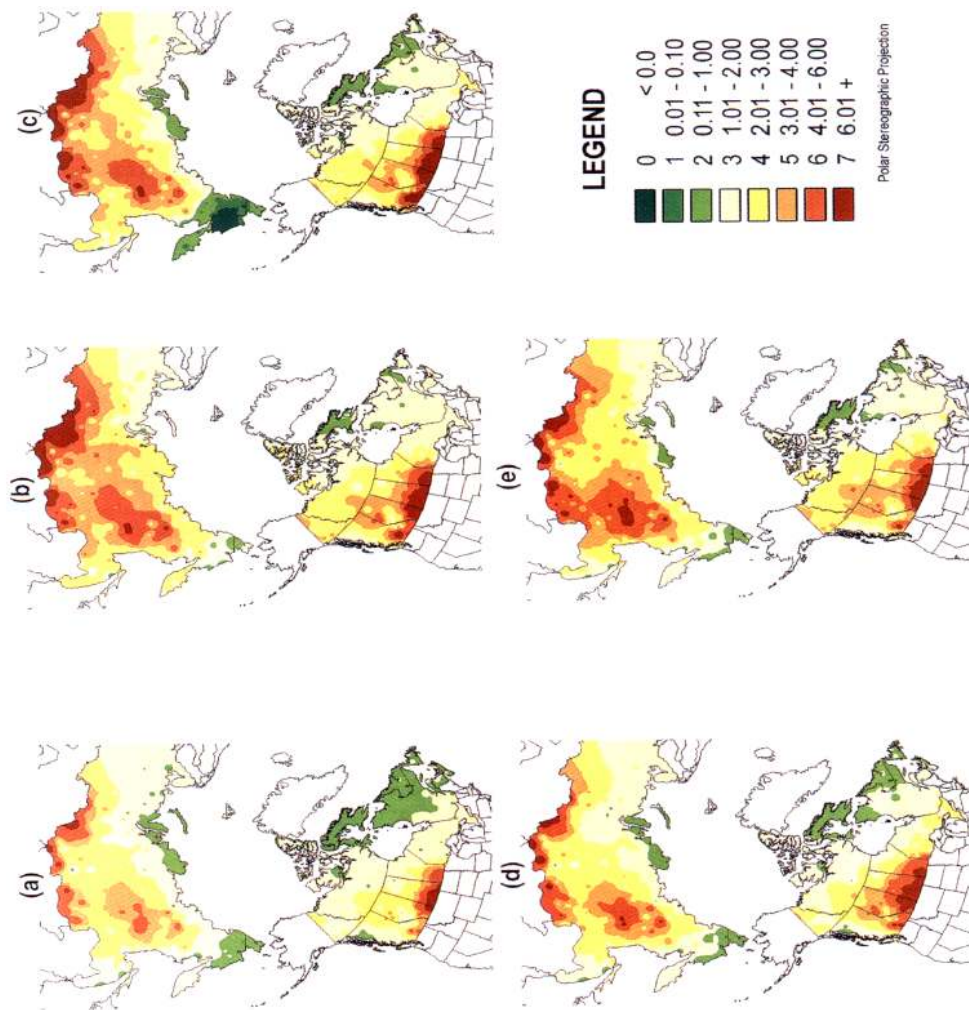
Figure 2. Average Seasonal Severity Rating (SSR) maps for Canada and Russia, showing (a) the 1980–1989 baseline SSR data, and projected $2 \times CO_2$ SSR maps using the (b) Canadian, (c) United Kingdom, (d) German, and (e) United States GCMs.
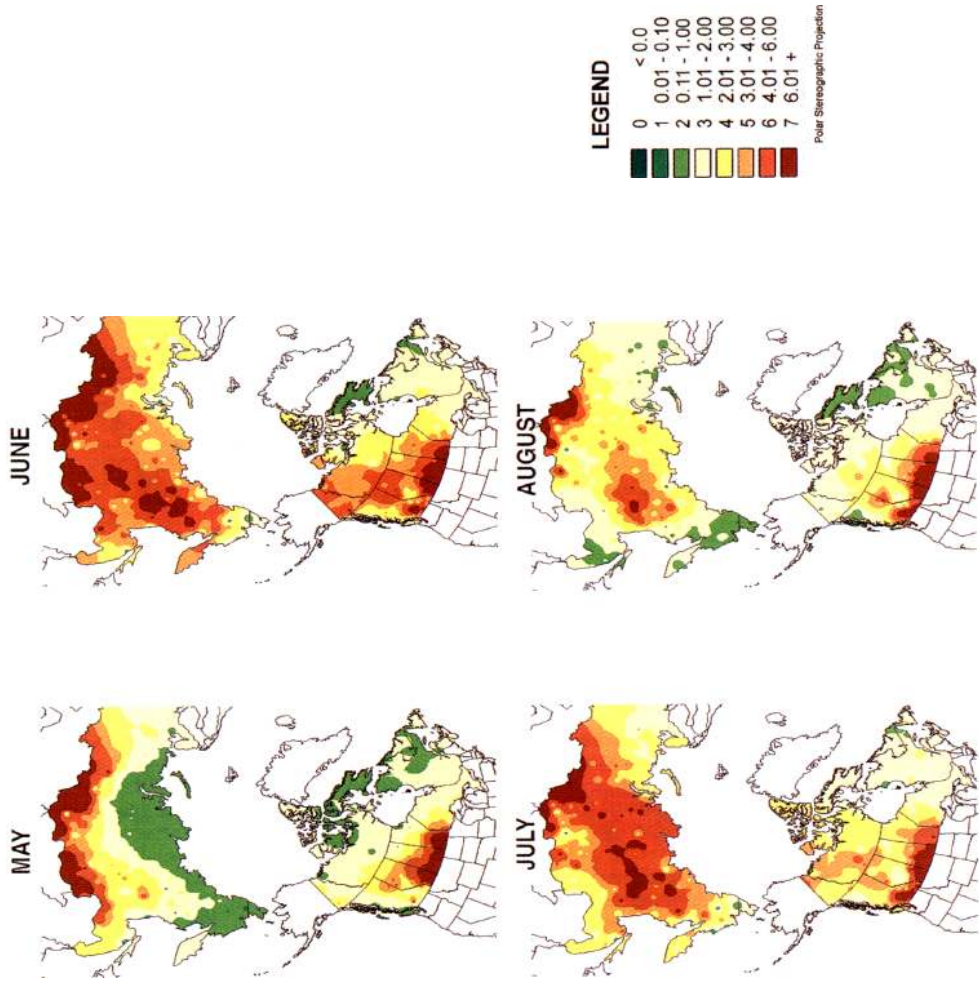
LEGEND

0	< 0.0
1	0.01 - 0.10
2	0.11 - 1.00
3	1.01 - 2.00
4	2.01 - 3.00
5	3.01 - 4.00
6	4.01 - 6.00
7	6.01 +

Polar Stereographic Projection

Figure 3. Average Monthly Severity Rating (MSR) maps for Canada and Russia under a 2 × CO$_2$ climate using the Canadian GCM.
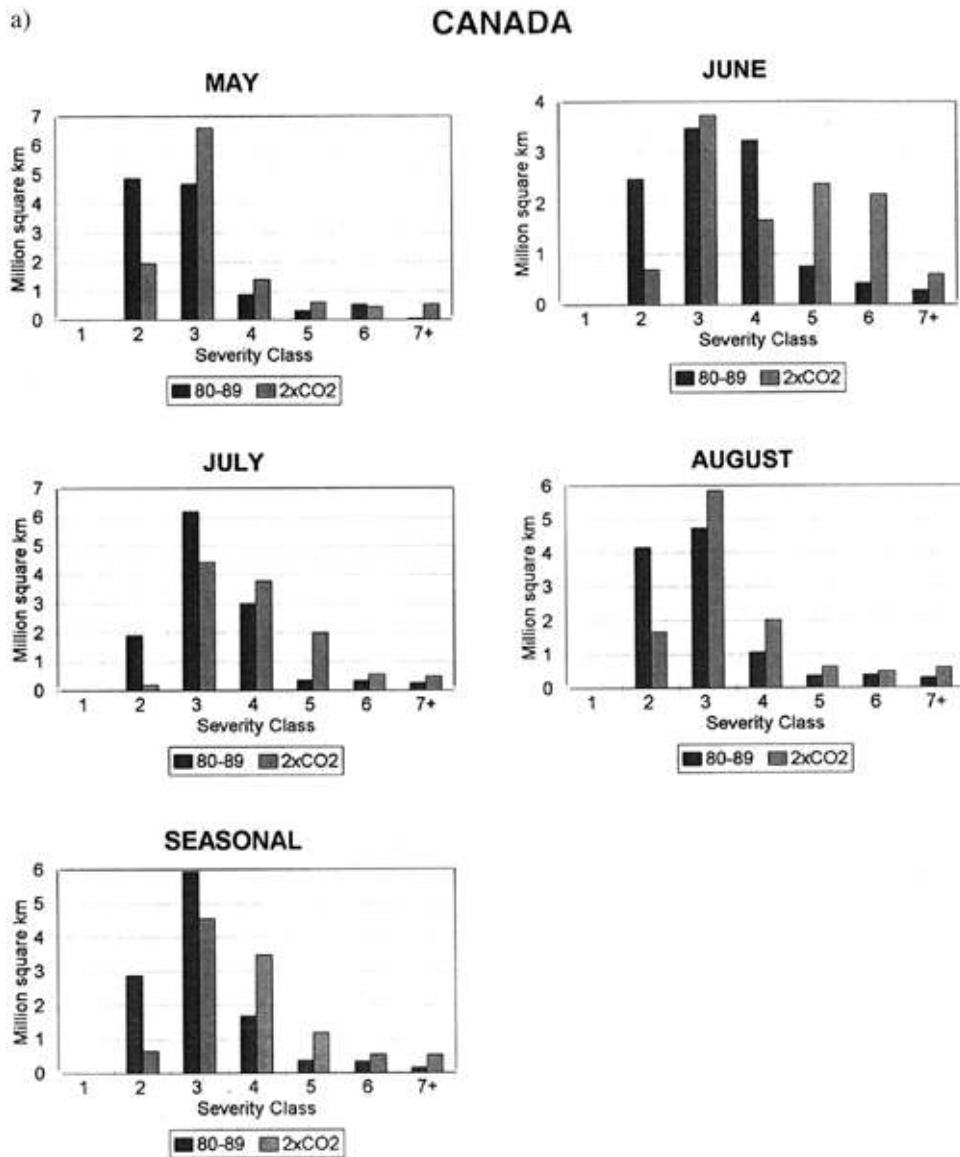
a)

CANADA

Figure 4a.

Doubled CO_2 MSR maps for May through August, using the Canadian Climate Centre GCM outputs, are illustrated in Figure 3. When compared to the monthly 1980s baseline data, the monthly progression under a $2 \times CO_2$ climate indicates an earlier start to the fire season, with significant increases in the geographical extent of extreme fire danger in May. The month of June shows the most significant increase, however, with virtually all of Siberia and western Canada under extreme
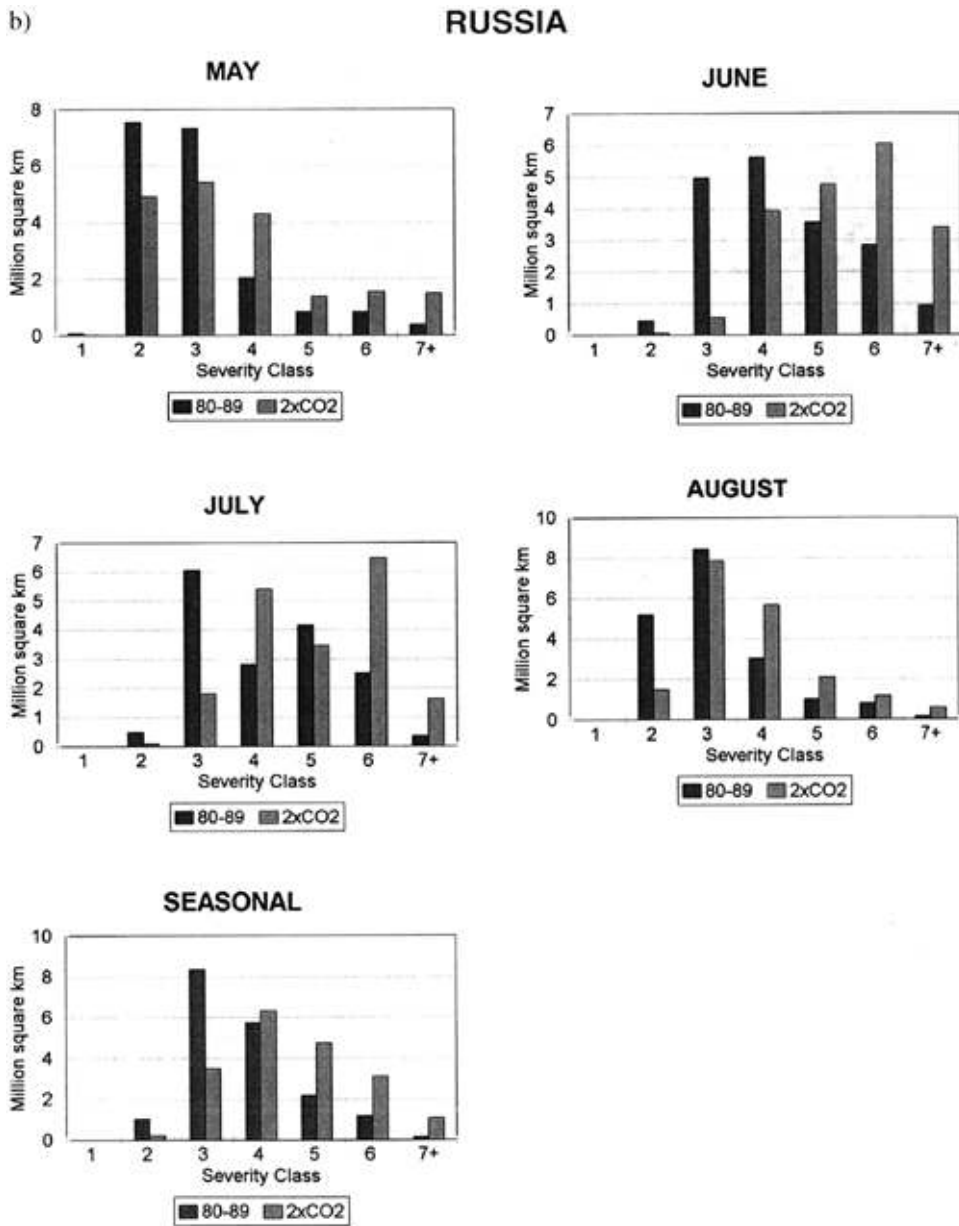
b)   **RUSSIA**

Figure 4b.

Figure 4. Comparison of the areal extent of Monthly Severity Rating (MSR) and Seasonal Severity Rating (SSR) classes in (a) Canada, and (b) Russia using the 1980–1989 baseline weather data and the $2 \times CO_2$ climate projected by the Canadian GCM.

fire danger conditions during that period. A more modest increase is observed in July and August. The seasonal pattern changes indicate an earlier annual start of high to extreme fire severity, and a later end to the fire season across Canada and Russia as a whole, although there are important regional variances from this pattern.

Changes in the area in each fire danger class are perhaps more important than absolute value changes in MSR. Figures 4a and 4b illustrate the dramatic changes in the areal extent of high to extreme fire danger in both countries under a doubled CO_2 climate. In general, there is a decrease in moderate MSR and SSR levels, and a significant increase in the area experiencing high to extreme MSR and SSR levels under a warmer climate. This is particularly true in June and July, but increases in the area under extreme fire danger (and therefore greatest fire potential) are common to all months. Significantly, two to three-fold increases are projected for Russia during the June–July period.

Although hampered somewhat by coarse spatial and temporal resolution, the four GCMs utilized in this study show similar increases in fire danger levels across much of west-central Canada and Siberia under a warmer climate. While shifts in forest types associated with climate change were not considered in this analysis, these increases in fire danger alone will almost certainly translate into increased fire activity, and, as fire management agencies currently operate with little or no margin for error, into large increases in area burned. The result will be more frequent and severe fires, shorter fire return intervals, a skewing of forest age class distribution towards younger stands, and a resultant decrease in the carbon storage of northern forests (cf. Kurz et al., 1995). A warmer climate, in combination with severe economic constraints and infrastructure downsizing, which will decrease the effectiveness and thus the area protected by fire management agencies, means a new reality in forest fire impacts is on the horizon. There is a strong need to continue modelling future climates, using higher-resolution models as they become available, so that future fire management planning can be accomplished in the most informed manner possible.

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