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PAST AND FUTURE CHANGES IN CANADIAN BOREAL WILDFIRE ACTIVITY

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Abstract. Climate change in Canadian boreal forests is usually associated with increased drought severity and fire activity. However, future fire activity could well be within the range of values experienced during the preindustrial period. In this study, we contrast 21st century forecasts of fire occurrence (FireOcc, number of large forest fires per year) in the southern part of the Boreal Shield, Canada, with the historical range of the past 240 years statistically reconstructed from tree-ring width data.

First, a historical relationship between drought indices and FireOcc is developed over the calibration period 1959–1998. Next, together with seven tree-ring based drought reconstructions covering the last 240 years and simulations from the CGCM3 and ECHAM4 global climate models, the calibration model is used to estimate past (prior to 1959) and future (post 1999) FireOcc. Last, time-dependent changes in mean FireOcc and in the occurrence rate of extreme fire years are evaluated with the aid of advanced methods of statistical time series analysis.

Results suggest that the increase in precipitation projected toward the end of the 21st century will be insufficient to compensate for increasing temperatures and will be insufficient to maintain potential evapotranspiration at current levels. Limited moisture availability would cause FireOcc to increase as well. But will future FireOcc exceed its historical range? The results obtained from our approach suggest high probabilities of seeing future FireOcc reach the upper limit of the historical range. Predictions, which are essentially weighed on northwestern Ontario and eastern boreal Manitoba, indicate that, by 2061–2100, typical FireOcc could increase by more than 34% when compared with the past two centuries.

Increases in fire activity as projected by this study could negatively affect the implementation in the next century of forest management inspired by historical or natural disturbance dynamics. This approach is indeed feasible only if current and future fire activities are sufficiently low compared with the preindustrial fire activity, so a substitution of fire by forest management could occur without elevating the overall frequency of disturbance. Conceivable management options will likely have to be directed toward minimizing the adverse impacts of the increasing fire activity.

Key words: climate change; climate simulations; drought reconstruction; forest fires; general circulation model; tree rings.

Introduction

There has been an increasing demand over the past decade for the implementation of sustainable boreal forest management practices in Canada that integrate ecological-based research (Burton et al. 2003). One approach relates to the application in silvicultural management of scientific-based knowledge on historical or natural disturbance dynamics. Management that favours landscape compositions and stand structures similar to those found historically should be able to maintain biodiversity and essential ecological functions. Bergeron et al. (2004) indicate that in fire-dominated landscapes, this approach is feasible only if current and future fire activities are sufficiently low compared with the preindustrial period, so a substitution of fire disturbance by silvicultural management can occur without elevating the overall frequency of disturbance. For instance, even-aged or low retention silvicultural systems could be used to create forest age structures that would exist under shorter fire-returning intervals (Bergeron et al. 2006). In the advent of greater fire activity, the adaptation options most recommended are to increase suppression effort, salvage logging, and regeneration enhancement, so as not to increase the probability of interference between fire disturbance and silvicultural management (Le Goff et al. 2005). Clearly, in the context of climate change, reconstructing past and forecasting future fire activity is of central importance for effective implementation of sustainable management strategies.

In the boreal forest, wildfire is a primary natural process that organizes the physical and biological

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attributes of forests, shapes their landscape diversity and influences their biogeochemical cycles (Weber and Flannigan 1997, McRae et al. 2001). The mosaics of their different vegetation types are to a large extent an expression of their respective fire regimes (fire regime encompasses fire intensity, frequency, seasonality, size, type [crown vs. surface], and severity [depth of burn] [Weber and Flannigan 1997]) and many species have adapted to fire (Burns and Honkala 1990). Weather influences daily wildfire characteristics because of its impact on fuel moisture and the effects of precipitation (particularly its frequency), relative humidity, air temperature, wind speed, and lightning (Flannigan and Harrington 1988, Flannigan and Van Wagner 1991, Harrington et al. 1991, Johnson 1992, Agee 1997, Weber and Flannigan 1997, Bergeron et al. 2001). Drought is particularly important as a control on the occurrence of forest fire; fires spread rapidly when the fuels are dry and the weather conditions are warm, dry, and windy. Despite the increasing importance of human activity as a source of fire ignition over the last few decades (Stocks et al. 2003), dry forest fuels and wind remain major contributors to large stand-replacing fires (e.g., Johnson et al. 1990, Masters 1990, Johnson 1992).

The warming trend in the northern hemisphere that started in the 1850s and accelerated in the 1970s has become a major issue worldwide (Intergovernmental Panel on Climate Change 2007). The enhanced greenhouse effect generated by a release of CO_2 and other greenhouse gases into the atmosphere is the most probable cause for this warming or at least a substantial amount of the warming (Mann et al. 1998, Meehl et al. 2003, Scafetta and West 2006, Intergovernmental Panel on Climate Change 2007). With a dynamic climate and the strong linkage between climate, weather, and forest fires, variations in wildfire activity due to changes in the climate are expected. Numerous studies documented the likely impacts of anticipated climate change on area burned in boreal Canada (e.g., Flannigan and Van Wagner 1991, Flannigan et al. 1998, 2005, Stocks et al. 1998, Bergeron et al. 2004, Bergeron et al. 2006). While the influence of climate change on fire disturbance must be viewed in a spatially dependent context, for given territories these projections are not always in agreement. Projections for eastern Canada for instance can range from decreasing fire activity in a changing climate (e.g., Bergeron et al. 2004) to large increases (e.g., Flannigan et al. 2005). Among plausible reasons for the discrepancies are the CO_2 emission scenarios under use (storyline of future development such as population growth, economic development, and technological change [Nakicenovic et al. 2000]), the models and underlying processes that drive them (empirical vs. process-based), the various sources of predictor variables (precipitation, temperature, fire weather indices, and so on), the sources of ignition (lightning vs. human-caused [Price and Rind 1994, Wotton et al. 2003]), the area of interest (regional vs. ecozone scales), and the reference period (preindustrial vs. current periods) with which the simulations are compared.

The reference period with which the simulations of fire activity are compared is amongst the most critical aspect for assessing climate change impacts on boreal forests, human health, and economic values. It is also a critical aspect for successful implementation of silvicultural management strategies in the context of climate change. Climate and wildfire are not constant but rather contain cycles with periods of several years to several decades. Studies based upon observational data limited to periods not exceeding a few decades may hence underestimate the historical range of fire variability. This is particularly true for the southeastern Canadian boreal forest where fire activity during the past 50 years was estimated to be rather low when compared with the previous 100 years or so (Bergeron et al. 2001, 2006, Girardin et al. 2006*a*, *b*). Probabilities for this region suggest that future fire activity will be greater than experienced in the past 50 years (Flannigan et al. 2005). But future fire activity could also be within the range of values experienced during the preindustrial period (prior to 1920 [Bergeron et al. 2004]). Many boreal forests have evolved with some level of fire. Nonetheless, although in such a scenario future fire activity may not be catastrophically different from the historical situation, the ecological and economic impacts of fire activity altered by climate change may still be severe (Flannigan et al. 2005).

The objective of this study is to determine whether projected changes in the occurrence of large forest fires on the southern part of the Boreal Shield of Canada by the end of the 21st century could exceed the historical range of the past 240 years. First, simulation of 21st century Drought Code variability over seven climatic regions is conducted using outputs from two global climate models (GCMs). The Drought Code is a component of the Canadian Forest Fire Weather Index (FWI) System (Turner 1972, Van Wagner 1987) and is used daily by fire management agencies across Canada to monitor fire danger. Second, simulations of drought variability are "pieced" to tree-ring based drought reconstructions covering the period 1768–1998 (Girardin et al. 2006*c*). Third, the historical relationship between drought and the number of large forest fires (hereafter FireOcc) developed over the calibration period 1959–1998 (Girardin et al. 2006*a*), together with the tree-ring based drought reconstructions and the GCM simulations, is used to estimate past (years 1768–1959) and future (years 1999–2100) fire occurrences. Last, time dependent changes in mean FireOcc and in the occurrence rate of extreme fire years are evaluated with the aid of advanced methods of time series analysis (ramp regression and kernel estimation).

Study Area

The study area covers the eastern Boreal Plains to the eastern Boreal Shield ecozones and covers most of the

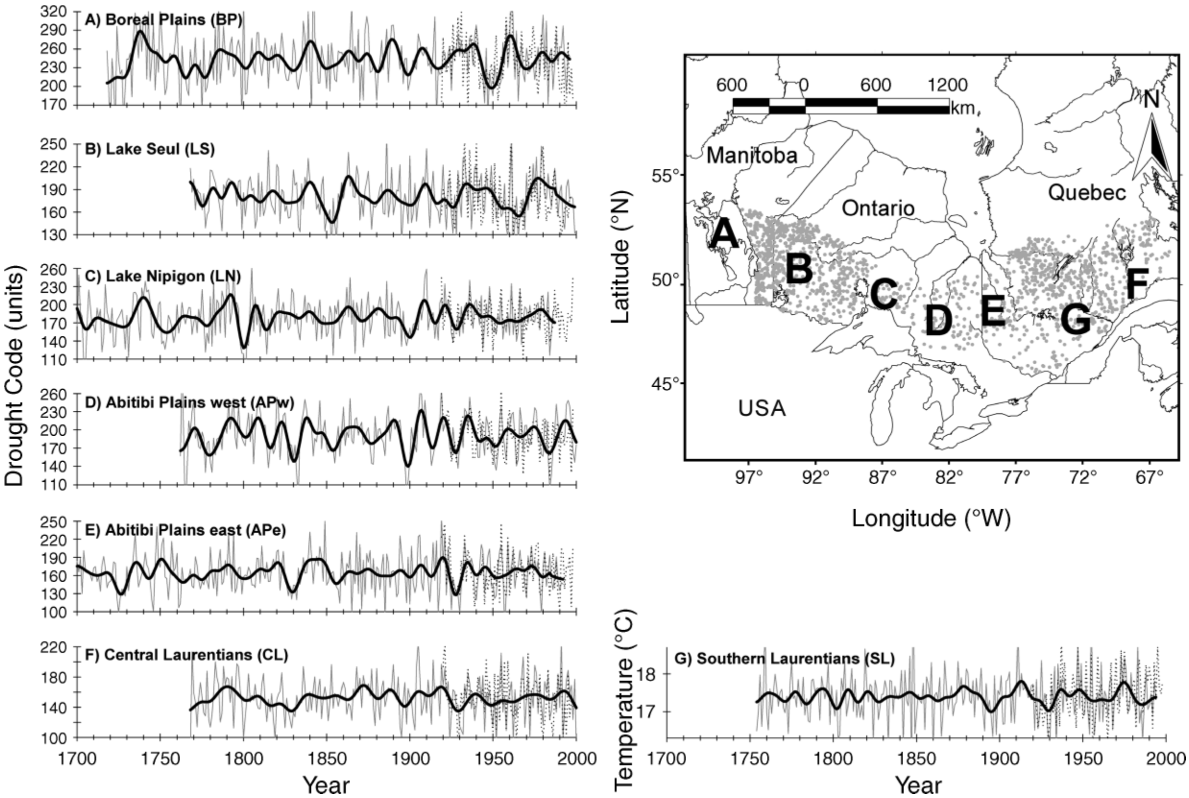

FIG. 1. (A–F) Reconstructions of the July mean of the daily Drought Code for a corridor covering boreal Manitoba to Quebec, Canada. The Drought Code scale ranges from soil saturation (zero units) to drought (>300 units). (G) Reconstruction of mean July and August temperature. Dotted lines show data obtained from meteorological stations (period 1913–1998); variance was adjusted to correspond to that of the reconstructions. Smoothed lines are 10-year polynomial fitting across the data. Light gray dots on the map indicate the location of large forest fires (size >200 ha) during the period 1959–1999 used to calibrate the fire occurrence (FireOcc) model.

boreal forest from western Manitoba to eastern Quebec, Canada (Fig. 1). The study area covers seven climate regions (Fig. 1) with boundaries approximating actual ecoregions defined by the Ecological Stratification Working Group (1996). These climate regions are the Boreal Plains (BP), the Lac Seul Upland and Lake of the Woods (LS), the Lake Nipigon (LN), the Abitibi Plains west and east (APw and APe), the Southern Laurentians (SL), and the Central Laurentians (CL) (Fig. 1).

All seven regions under study have a subhumid to humid mid-boreal ecoclimate (west to east gradient), marked by warm summers and cold, snowy winters according to the Ecological Stratification Working Group's (1996) regional classification. In regions BP and LS, average annual temperatures range between –1.0°C and 1.0°C, whereas eastern regions LN to CL temperatures range between 0°C and 1.5°C. The average summer temperature is similar across the seven regions, approximately 12.5°–14.0°C. The average winter temperatures are more variable, ranging from –16.0°C in region BP to –11.0°C in region SL. The average annual precipitation ranges from 450 mm in the west to 1600 mm in the east. In the study area, most of the annual precipitation falls between the months of June and October (Environment Canada 2002).

DATA AND METHODS

This section is divided as follows. First, we describe the data used as predictors of past, current and future FireOcc. These data include six tree-ring based reconstructions of the July mean of the daily Drought Code and of mean July and August temperatures (period 1768–1998), fire statistics (period 1959–1998), and gridded daily temperature and precipitation data collected from GCMs (period 1961–2100). Second, the statistical procedure employed in the prediction of FireOcc is described. We end with a description of statistical approaches for assessing long-term changes in the mean and in the occurrence rate of extreme fire years. Detailed descriptions of the current study data and methods have been published (Mudelsee 2000, Mudelsee et al. 2004, Girardin et al. 2006*a*, *c*).

Description of the fire data

Forest fire data from the large fire data base (LFDB; Stocks et al. 2003) are used in this study to calibrate the FireOcc model. These large fires (size >200 ha) represent only a very small percentage of the fires but account for ~97% of the area burned in Canada. The LFDB contains information on start location, estimated ignition date, cause, and size of each fire. It is worth mentioning that the quality of forest-fire statistics varies over both time and space. Even though weather/climate is the most important factor in fire activity, other factors such as changes in fire suppression, land use, ignition, and fuel can influence fire statistics (Podur et al. 2002). The area effectively under fire management is also an increasing function of time in most provinces. It is widely accepted that not all the fires that occurred in lower priority areas were detected, reported, and included in the annual fire statistics.

Fires that occurred in 10 ecoregions of the Boreal Shield (Fig. 1; namely ecoregions 90, 91, 92, 93, 94, 96, 97, 99, 100, and 101) were compiled and a time series of FireOcc (number of large fires per year) covering the period 1959–1998 was created. The use of FireOcc as the predictand (i.e., the variable to predict) was preferred over area burned as the relationship between historical FireOcc and drought was shown to be robust (Girardin et al. 2006*a*). The use of an aggregate FireOcc record for the whole study region instead of regional series was also preferred. Fire is highly variable among years and the use of a large number of samples provided some statistical smoothing that improved the final calibration results.

A Shapiro-Wilk normality test indicated right-skewness (Zar 1999) in the FireOcc frequency distributions ($P = 0.001$, where P values below 0.050 are considered small enough to declare the fit with the normal curve poor). The logarithmic transformation was found to provide an adequate data transformation to meet the approximate normality requirement ($P = 0.374$).

Tree-ring-based drought reconstructions

Six tree-ring-based reconstructions of the July mean of the daily Drought Code are used in the present work (Fig. 1). Five of these were previously published data (Girardin et al. 2006*c*); the CL reconstruction is an unpublished record (M. P. Girardin, *unpublished manuscript*). A seventh reconstruction (region SL; Girardin et al. 2006*c*) was one of the mean July and August temperatures (hereafter also referred to as "drought proxy" for simplicity).

The Drought Code was developed to represent the net effect of daily changes in evapotranspiration and precipitation on cumulative moisture depletion in soils. It reflects the moisture content of organic matter averaging about 18 cm thick and 25 kg/m^2 dry mass, for a bulk density of 138.9 kg/m^3. Because soil loses moisture exponentially, the Drought Code was found to be quite well suited to represent certain slow-drying, heavy fuels (time constant about 52 days). The equation linking the Drought Code (DC) to its moisture equivalent (Q) from Van Wagner (1987) is

$$Q = 800\ e^{-\mathrm{DC}/400}. \tag{1}$$

The 400 constant in Eq. 1 represents the maximum theoretical moisture content of the fuel represented by the Drought Code, which roughly corresponds to the water-holding capacity of the soil (100 mm) (Van Wagner 1987). There are no absolute guidelines as to the meaning of the Drought Code values but generally speaking, values below 200 are considered low and 300 may be moderate in most parts of the country. A Drought Code rating of 300 or more indicates that fire will involve burning of deep sub-surface and heavy fuels.

The drought reconstructions were developed from a network of 126 well-replicated site tree-ring width chronologies originating mainly from the Boreal Shield (site tree-ring width chronologies are defined as averages of annual ring width measurements for one to several cores per tree and for several trees growing on similar ecological sites). Each drought reconstruction was developed independently from the others, that is, there was no data overlap between regions. The rationale linking tree growth to the Drought Code is that assimilation of carbohydrates and optimal tree growth occur only if soil moisture is sufficient to maintain foliage water potential and minimize vapor pressure deficits (Girardin and Tardif 2005). By using a linear model relating tree growth to Drought Code indices, past drought values can be inferred from multi-century tree ring chronologies. In turn, the inferred drought records can be calibrated against fire statistics (e.g., Westerling and Swetnam 2003). In some circumstances, the relationship between tree growth and the Drought Code may be of little use for inferring past drought variability. This was the case with the SL region and, alternatively, a mean July and August temperatures reconstruction was used. For the purposes of the present study, four of the six Drought Code reconstructions were updated through 1998 using Drought Code values obtained from meteorological data.

The drought reconstructions used in the current study provide meaningful information about drought severity changes occurring from year-to-year and decade-to-decade. However, one should note that they do not contain information about secular changes (Girardin et al. 2006*c*). Tree-ring width measurement series represent a mixture of climatic and non-climatic signals and nearly always include an age/size-related trend that needs to be removed. The "detrending" procedure has the caveat of also removing long-term trends that could result from secular climate changes (Cook and Kairiukstis 1990, Cook et al. 1995). In the data current to this study, 99% of the variance contained in periods of <19 years was preserved, and 50% of the variance in periods of <60 years was preserved (Girardin et al. 2006*c*). The mean length of measurement series (mean age of 137 years) was considered insufficiently long to allow robust reconstruction of lower frequency variations in drought severity.

Simulated drought data

Prediction of future FireOcc is made using simulated daily temperature and precipitation data collected from the CGCM3 (Flato et al. 2000) and ECHAM4 (Roeckner et al. 1996) global climate models. These models are time-dependent numerical representations of the atmosphere and its phenomena over the entire Earth, using the equations of motion and including radiation, photochemistry, and the transfer of heat, water vapor, and momentum. Future climate scenarios are built based on the effects of various concentrations of greenhouse gases and other pollutants within the atmosphere on the earth–atmosphere system.

Data were collected from CGCM3 runs 1961–2000, 2046–2065, and 2081–2100, and from the ECHAM4 runs 1850 to 2100; for comparison purposes the periods common to both data sets are used in this paper. Model resolutions used are the T63 version for CGCM3 (2.8° latitude/longitude and 31 levels in the vertical) and the T42 version for ECHAM4 (2.8° latitude/longitude and 19 levels in the vertical). Daily data were collected from four to six cells located in and near each of the seven regions (Appendix A). The daily Drought Code was then computed at each cell. Next, July monthly means of the Drought Code were computed for each region after weighting each cell by the amount of study area within the cell (Appendix A). Finally, Drought Code records spanning from 1768 to 2100 were created after "piecing" together the 1768–1998 Drought Code reconstructions with the 1999–2100 simulations (Appendix B; adjustments to the mean and variance were made so that reconstruction and simulation data had equal mean and variance over their common period 1961–1998). The temperature record was developed using the same approach.

Four scenarios of projected changes in greenhouse gas emissions (Nakicenovic et al. 2000) are used in this study (from "worst" to "best"-case scenarios): A2, A1B, B2, and B1 (Fig. 2). Each scenario reflects a specific storyline of future development such as global population growth, economic development, and technological change. The storylines describe the relationships between the forces driving greenhouse gas and aerosol emissions and their evolution during the 21st century (Fig. 2; descriptions of scenarios are *available online*):[4]

1) A2 storyline (hereafter intense forcing): a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines.

2) A1B storyline (intense forcing): a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies.

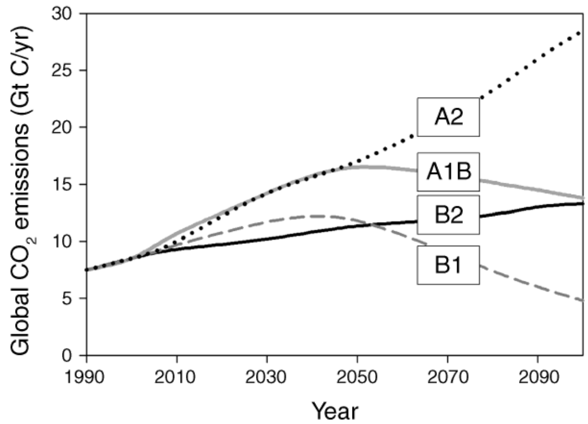

FIG. 2. Total global annual carbon dioxide (CO_2) emissions from all sources (energy, industry, and land-use change) from 1990 to 2100 for the four scenarios described in *Data and methods: Simulated drought data*, from "worst" to "best": A2, A1B, B2, and B1.

3) B2 storyline (intermediate forcing): a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

4) B1 storyline (intermediate forcing): a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.

These storylines are intended to cover a wide spectrum of alternative futures to reflect relevant uncertainties and knowledge gaps associated with climate change issues (Nakicenovic et al. 2000).

Calibration and verification of the FireOcc model

A stepwise multiple regression employing a backward selection was used to calibrate the log-scaled FireOcc data (period 1959–1998):

$$Y_{\log j} = \alpha + \beta_1 X_{1j} + \beta_2 X_{2j} + \cdots + \beta_m x_{mj} + \varepsilon_j \qquad (2)$$

where $Y_{\log j}$ is the fire data, j is the year, X_j the Drought Code and temperature records (present and prior year lags: total $m = 14$ predictors), β the regression coefficients, and ε_j the error. A prior lag is included in order to take into account a possible overwintering of drought (probability that a current drought persists the following year as a result of insufficient winter precipitation [Girardin et al. 2006*a*]). The stability of the regression model is tested after conducting two subcalibrations of the period 1959–1978 and 1979–1998 using the selected variables in Eq. 2. The strength of the relationship between estimates and observations over the independent verification periods 1979–1998 and 1959–1978, respectively, is measured by the reduction of error (RE), Pearson correlation coefficient, and the product means test (PM) discussed in Cook et al. (1994) and

[4] ⟨http://sedac.ciesin.org/ddc/sres/index.html⟩

Cook and Kairiukstis (1990) (see Appendix C). The RE provides a sensitive measure of reconstruction reliability. Whenever RE is greater than zero, the prediction is considered as being a better estimation of fire occurrence than the calibration period mean. A significant PM test result indicates that the magnitude and the direction of these changes are statistically significant. After development of the empirical FireOcc model and verification of its predictive skills, the regression coefficients estimated for the calibration period are applied to the period from 1768 to 2100 to predict past and future log-scaled FireOcc. Finally, the log-scaled FireOcc estimates are back-transformed to arithmetic units (ha) using the conversion function (Baskerville 1971):

$$\hat{Y}_j = 10e^{\hat{Y}_{\log j}+\hat{\sigma}^2/2} \qquad (3)$$

where $\hat{\sigma}^2$ is the variance of FireOcc estimates. This method has been applied at several scales across Canada (Girardin et al. 2006*a*, *c*, Girardin 2007, Girardin and Sauchyn 2007) and for the current study area, the produced FireOcc estimates significantly correlate against a stand-establishment record obtained from dendrochronological dating (see Girardin et al. 2006*a*). The program used for the stepwise multiple regression analyses is SYSTAT 9.1 (alpha-to-enter and alpha-to-remove were set at 0.05 [Systat 1998]). The program used for calculation of the RE and PM verification statistics is VFY (Holmes 1999).

Transitions in mean FireOcc

A parametric change-point trend model is fitted to the FireOcc estimates to detect changes in the mean. The ramp model (Mudelsee 2000) is a three-phase function consisting of a constant part, a linear change (increase or decrease), and again a constant part. A least-squares criterion is employed to define the best-fitting ramp to a record. The optimum FireOcc values are found by setting the first derivative of the least-squares sum equal to zero and solving the resulting normal equations. The optimum change-point times are found by a brute-force search: all possible combinations of transition times are evaluated, and the solution that yields a minimum sum of squares is retained. To determine the accuracy of the ramp fits, the procedure is combined with nonparametric bootstrap resampling that takes autocorrelation and non-normal error distributions into account (Mudelsee 2000). That means the method is robust against the effects of skewness, which is often found in extreme value time series. The software, RAMPFIT (Mudelsee 2000), has been previously used to quantify climate transitions, for example, the Northern Hemisphere Glaciation (Mudelsee and Raymo 2005). RAMPFIT is available in the Supplement.

Occurrence rate estimation of extreme fire years

Changes in the occurrence rate of extreme fire years are analyzed over the period 1768–2100 using kernel functions. Extreme fire years are defined as years during which FireOcc exceeds a detection threshold computed from a running median smoothing ($2k + 1$ points) and the median of absolute distances to the median (factor z). This approach is particularly useful when both the background state and interannual variability change through time (Mudelsee 2006). Kernel estimation allows detailed inspection of time-dependent event occurrence rates and assessment of significant changes with the help of confidence bands. We used a Gaussian kernel, K, to weigh observed extreme fire occurrence event dates, $T(i)$, $i = 1, \ldots, N$ (total number of events), and calculate the occurrence rate, λ, at time t as

$$\lambda(t) = \sum_i K\{[t - T(i)]/h\}/h. \qquad (4)$$

The number of extreme fire occurrence events under analysis was set to equal the highest 15% percentile. The selection of the bandwidth, h, was guided by cross-validation (Mudelsee et al. 2004). Confidence bands (90%) around $\lambda(t)$ were determined using the following bootstrap technique. N simulated events were drawn from $T(i)$ with replacement and simulated λ calculated. This procedure was repeated 10 000 times, and a percentile-t confidence band was calculated. The confidence bands helped us to assess whether highs and lows in the occurrence of extreme fire events are significant or not. Detected trends in occurrence rate were confirmed for the measured interval using the statistical test described by Cox and Lewis (1966). This parametric procedure tests the null hypothesis "constant occurrence rate" against one-sided alternatives such as "increasing occurrence rate." One seeks to disprove the hypothesis of a constant occurrence rate when the P value is lower than 0.05. Kernel occurrence rate estimation with bootstrap confidence band construction was introduced into the analysis of climate extremes by Mudelsee et al. (2003); a detailed description is given by Mudelsee et al. (2004). We used XTREND (Mudelsee 2002) for occurrence rate estimation and used CLIM-X-DETECT (Mudelsee 2006) for detection of extremes.

Results and Discussion

Drought Code simulations

For means of simplicity, this work strictly focuses on changes in the July average of daily Drought Code data. The Drought Code is cumulative and hence the six July Drought Code reconstructions presented in Fig. 1 approximate the average moisture content of deep and compact organic layers for a season approximating May to July. Over 78% of the total area burned in Canada does so during this season (Stocks et al. 2003). We nevertheless caution that the following analyses and interpretations may omit variability in the spring and late summer season.

Human-caused climate change in the boreal forest is usually associated with increased temperature, drought, and fire activity (Gillett et al. 2004, Flannigan et al.

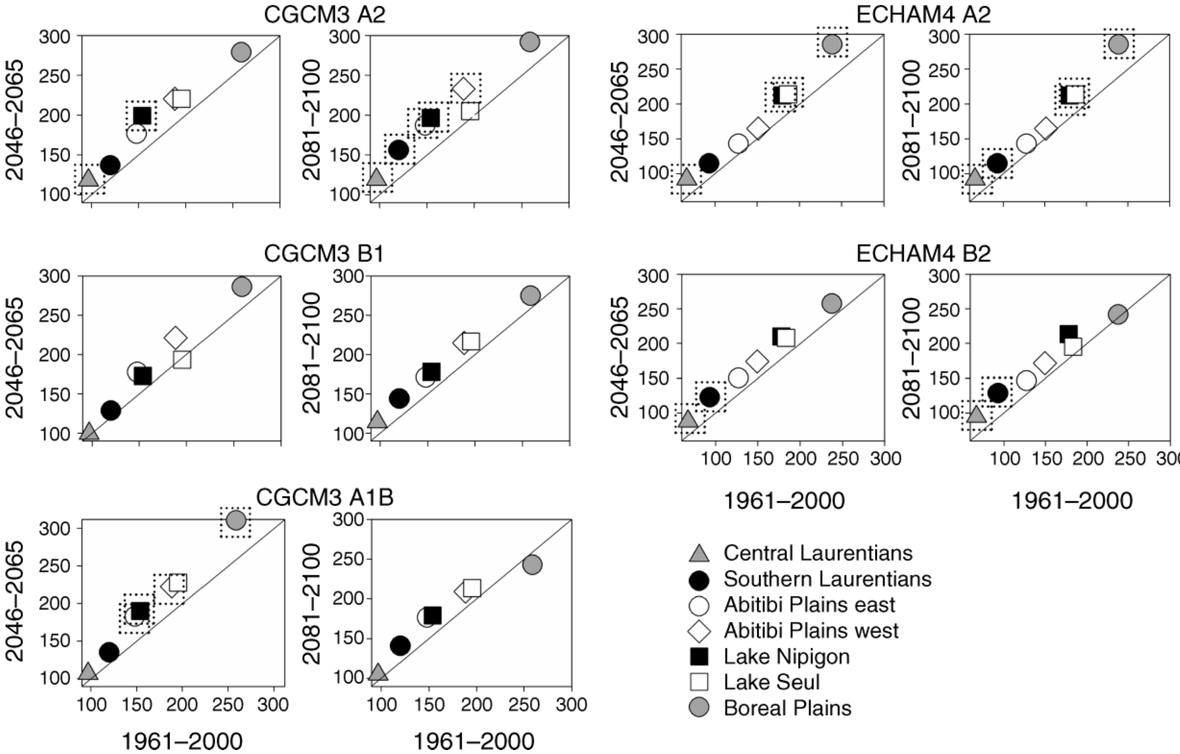

FIG. 3. Dispersion diagrams showing non-adjusted averages of the July Drought Code over horizons 1961–2000, 2046–2065, and 2081–2100 as simulated using output from the CGCM3 and ECHAM4 models described in *Data and methods: Simulated drought data*. Abbreviations A2, A1B, B1, and B2 denote the four scenarios of projected changes in CO_2 emissions. Each scenario reflects a specific storyline of future development such as global population growth, economic development, and technological change (Fig. 2). The dotted box denotes significant differences ($P < 0.05$) in mean drought severity according to t statistics. The diagonal line denotes the 1:1 ratio.

2005, Bergeron et al. 2006). Plummer et al. (2006) predicted increasing June to August daily mean temperatures by 1.5°–2.5°C over the area under study by years 2041–2060. Changes in precipitation were predicted to be more variable, from no change in western regions to increases by up to 20% in the east (also see Intergovernmental Panel on Climate Change 2007). Trends like these are also typical of CGCM3 and ECHAM4 simulations, and are well reflected in our forecasts of future Drought Code severity (Fig. 3). July mean of the daily Drought Code is predicted to increase significantly in climatic regions south of Hudson Bay (Fig. 3). Of the 60 Drought Code ratios computed, only one ratio is below the 1:1 line. Those regions for which statistically significant increases are noted are the Central and Southern Laurentians, Lake Seul Upland, and Boreal Plains in the A2 scenario run of ECHAM4. Increases predicted by the CGCM3 are uniformly distributed across the seven regions and within the range predicted by ECHAM4. The most severe increases are predicted by the A1B scenario over horizon 2046–2065 and A2 over 2081–2100. The current simulations of the Drought Code suggest that the increase in precipitation projected toward the end of the 21st century will be insufficient to compensate for increasing temperatures and will be insufficient to maintain potential evapotranspiration at current levels, no matter which scenario of greenhouse gas emissions is considered. How do these increases in drought severity translate in FireOcc?

Calibration and verification of the FireOcc model

A total of 58.9% of the variance in FireOcc observations over the period 1959–1998 is accounted for by estimates obtained from the equation

$$Y_{\log j} = -1.3201 + 0.0048\text{LS} + 0.0034\text{APe} + 0.0073\text{APw}_{\text{lag}} \quad (5)$$

where LS, APe, and APw are regional drought reconstructions of the Lake Seul Upland and Abitibi Plains west and east regions and $Y_{\log j}$ is FireOcc of the whole study area. While current year drought accounts for the largest amount of variation in FireOcc, part of the variance can also be explained by drought conditions of the previous year (lag) (also see Girardin et al. 2006*a*). Verification statistics of the strength of the sub-calibration models are shown in Table 1. These statistics indicate significant predictive skills of the FireOcc estimates. Positive PM and significant correlation coefficients indicate tendencies for the estimates to reproduce with confidence high frequency variations in

TABLE 1. Calibration and verification statistics of the statistical reconstruction of fire occurrence (FireOcc).

Statistic	Calibration period		
	1959–1998	1959–1978	1979–1998
R^2	0.587	0.722	0.610
SE	0.246	0.226	0.229
First-order autocorrelation of residuals	0.202	−0.100	0.126
Durbin-Watson statistic	1.566	2.066	1.577
Period on which the model was verified		1979–1998	1959–1978
Correlation, r†		0.760	0.830
RE‡		0.152	0.470
PM§		1.910	2.457

† Significant at $P < 0.05$ if $r > 0.378$.

‡ Reduction of error (RE) is a measure of shared variance between the observed and modeled series but is usually lower than the r^2. The RE uses the calibration period mean as the standard of reference for calculating the total sum of instrumental squared deviations, allowing it to detect changes in the mean of the reconstructed values from the calibration period mean. A positive value (RE > 0) signifies that the regression model has some skill.

§ A significant product means test (PM) result indicates that the magnitude and the direction of year-to-year changes are statistically significant (considered significant at $P < 0.05$ if PM > 1.73).

actual data; confidence for reproducing lower frequency variations and long-term trends is poorer (low RE statistic for the 1979–1998 verification period in spite of a high correlation; discussed below). Sensitivity analyses in which calibration of Eq. 1 was conducted on the leading principal component (PC1) of the seven drought records (accounting for 40.7% of the variance in FireOcc observations) and on PC1 of drought indices obtained from meteorological weather stations (accounting for 28.4% of the variance in FireOcc observations) confirmed the robustness of the results and later conclusions (Appendix D; also see Girardin et al. 2006*a*).

The regression coefficients estimated from Eq. 5 were applied to data collected from the CGCM3 and ECHAM4 models and predictions of current and future FireOcc were made (Fig. 4). Unanimously, all predictions indicate increases of FireOcc in a changing climate. But the timing of this increase is largely dependent on the scenario of greenhouse gas emissions being considered. Furthermore, some scenarios (B1 and B2 for instance) suggest that the yearly magnitude of future FireOcc would be within the range observed during the past 40 years or so. Without regards to the interannual variability, it can be affirmed from Fig. 5 that the relationship between total global emissions of carbon dioxide (tied to global economic development) and FireOcc is one of a net increase.

Multicentury FireOcc variability

The regression coefficients estimated from Eq. 5 were applied to the "pieced" drought records covering the continuous 1768 to 2100 period and prediction of FireOcc was made for the whole period. We caution that merging of the various sources of data may have introduced biased changes in the variance and mean, particularly after transforming to nonnormal distributions. As means of verification, the two-sample Kolmogorov-Smirnov test was used to compare the cumulative distribution functions of the tree-ring and GCMs inferred FireOcc data (in arithmetic units) over their common period 1962–1998. The test assumes that both samples come from exactly the same distribution. Analyses were conclusive ($P > 0.20$, where $P < 0.05$ indicates that the two distributions differ significantly) and hence the "pieced" FireOcc record may be analyzed with some level of confidence. Note that the kernel estimation of occurrence rate (discussed later) accounts for changes in background and variance states and hence reduces this bias.

So will future fire occurrence exceed the historical range? The results obtained from our approach suggest high probabilities of having future levels reach the upper limit of the historical range. Ramp functions applied to the FireOcc estimates show striking changes in mean in the context of rapid climate change (Fig. 6), with significant increases during the 21st century. Predictions indicate that by the horizon 2061–2100, the median (i.e., typical) number of large forest fires per year could increase by 39% (ECHAM4 B2 scenario run) to 61% (A2 scenario run) when compared with the 1901–1940 and 1781–1820 reference periods (see Table 2). If considering the full 1999–2100 horizon, increases range from 34% to 55% when compared with 1795–1896 and 1897–1998, respectively. The occurrence rate of extreme events and the associated bootstrap confidence intervals also support these conclusions. These analyses (Fig. 6b, d) indicate low occurrence rates of extreme fire years during the second half of the 19th century and again during the late 20th century. The kernel occurrence rate estimates found one year of extreme fire conditions for every 19 years during the 1860s–1870s and 16 years during the 1970s–1980s. This contrasted with extreme fire activity as high as one event for every five years during the 1770–1820s and one for every six years

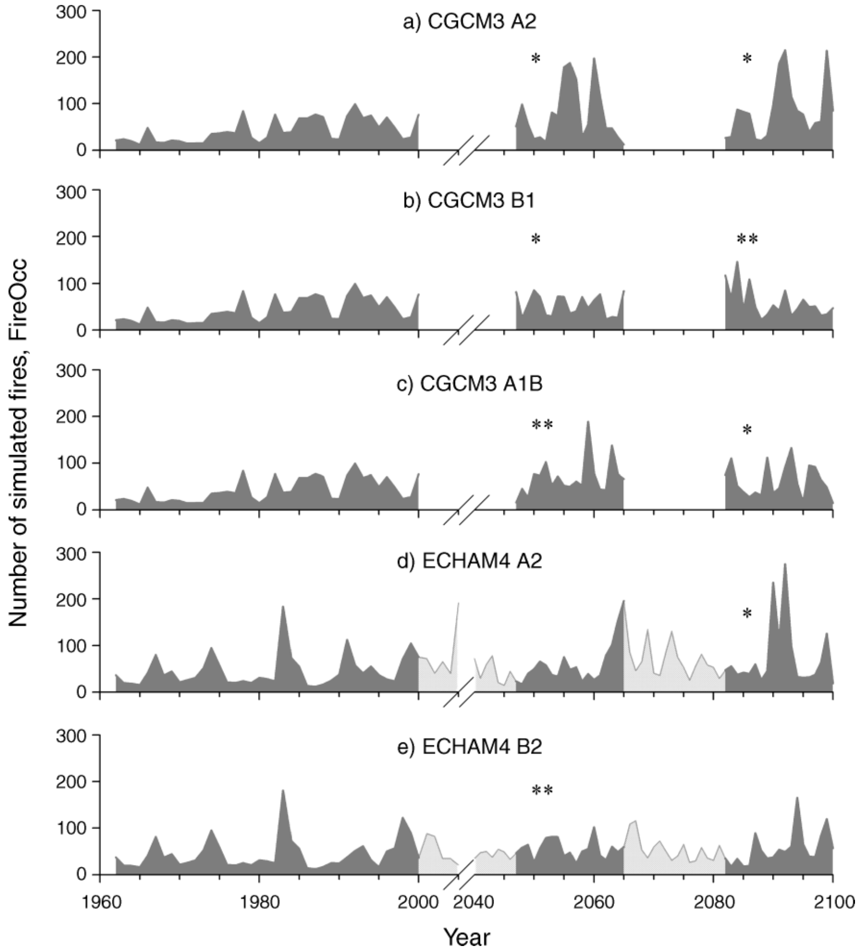

FIG. 4. Simulated occurrences of large forest fires (FireOcc). FireOcc estimates were computed using data collected from CGCM3 runs 1961–2000, 2046–2065, and 2081–2100, and from the ECHAM4 runs 1850–2100 (note that for CGCM3 1961–2000, the same run is used in panels a–c). Significant increases from the reference period 1962–2000 are indicated by one (95% level) and two (99% level) asterisks (tested using the nonparametric *t* test; only those periods common to all simulations (gray shaded) were tested for significance).

during the 1920s. Estimates of occurrence rates for the 21st century in the B2 scenario appear within the range of the historical period (before 1850) (Fig. 6d): one event for every six years in the mid-21st century and one for every five years in the late century. Conversely, the A2 scenario run yield occurrence rates of extreme fire years higher than seen prior to 1850 (Fig. 6b): one event for every four years by the late 2070s, which would be unprecedented. The upward trend of extreme fire years during the 21st century is not significant at the 95% level if considered in the context of the whole 1769–2100 period ($P = 0.470$). However, it is accompanied by extreme fire years of magnitudes unseen during the historical period. In regard to CGCM3 runs, it is rather difficult to say with the short time intervals whether future occurrence rates will be higher than during the historical period (Fig. 7). They are seemingly higher than during the late 20th century, and their upper limit could well be as high as that in earlier centuries, supporting the conclusion drawn from the ECHAM4 runs.

A potential source of bias includes the failure of the FireOcc estimates to adequately model century-long changes in fire activity. The tree-ring width measurement samples used to infer past drought conditions (and hence the FireOcc estimates) were detrended using flexible curve fitting (Cook et al. 1995) such that mainly interannual and decadal changes were preserved (see *Methods* section). The low RE statistic obtained in the FireOcc calibration–verification scheme could partly be related to the loss of the low-frequency bandwidth (Table 1). This weakness may distort the true magnitude of the 21st century changes. As means of verification of the bias' extent, the FireOcc estimates were compared with a recent statistical reconstruction of the area burned in the province of Ontario (Fig. 8). These area burned estimates were inferred from 25 multicentury-long tree-ring width chronologies covering AD

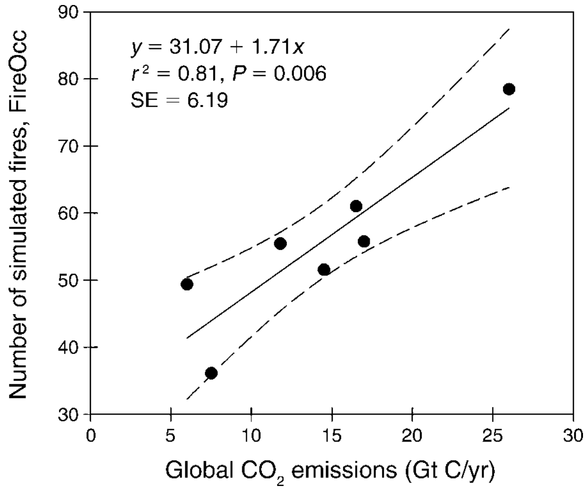

FIG. 5. Typical number of large forest fires per year (median FireOcc) simulated from CGCM3 data over periods 1962–2000, 2047–2065, and 2082–2100 (total of seven FireOcc simulations; refer to Fig. 4) plotted against the corresponding storylines of total global annual carbon dioxide (CO_2) emissions. Values used for CO_2 emissions were those of years 1990, 2050, and 2090 (refer to Fig. 2). A least-squares linear regression (solid line) with 95% confidence intervals (dashed lines) is shown.

1781–1982 and distributed largely across Ontario. The area burned estimates account for 39.5% of the variance in the observed area burned in Ontario recorded from 1917 to 1981. In contrast to the FireOcc estimates, area burned estimates contain a larger frequency bandwidth as a more conservative detrending procedure was employed in the treatment of the tree-ring width measurement samples (cubic smoothing splines of 66% of the ring-width series length for area burned estimates as opposed to cubic smoothing splines fixed at 60 years for FireOcc estimates). In spite of the less conservative detrending, the FireOcc estimates do not diverge significantly from estimates of area burned in Ontario (Fig. 8). Detrending of the ring-width series therefore does not appear to constitute an important source of bias to this study.

Limitations and challenges

We caution that the predicted FireOcc increase might not be widely distributed across the corridor under study and this is inherent to the large spatial variability in climate and fire activity (Fig. 1). First, the influence of temperature on moisture and fuel availability would cause fire occurrence to increase particularly in western Ontario and eastern boreal Manitoba, where high correlation between FireOcc estimates and temperature exists (Fig. 9). The strong covariance between the current FireOcc record and the Ontario area burned reconstruction (Fig. 8) strengthens the possibility that FireOcc estimates are more representative of fire activity variability in the province of Ontario than elsewhere (FireOcc estimates indeed share 21.8% of common variance with observed area burned in Ontario over 1917–1998). Second, fire activity is known for being highly variable in the spatial domain and the greatest fire activity occurs in regions west of our study area (Stocks et al. 2003). This is due to a combination of fire-prone ecosystems, extreme fire weather (a continental climate), and frequent lightning activity. As such, this region is likely to be weighted accordingly in the FireOcc estimates (Fig. 9). Furthermore, estimates of future area burned in Quebec (Bergeron et al. 2006) suggested that while fire activity under a warmer climate would be greater in many regions of this province, it could still be below the historical area burned (as reconstructed from dendrochonological dating of forest stands). Until it can be shown otherwise, the current results should be interpreted with caution and not directly applied to the entire corridor under study.

Additionally, the conclusions from this work should be limited to the impact of late-spring and summer climate variability on forest fire activity. Factors that are not directly taken into account in the seasonal drought severity component could modulate the projected increase of FireOcc over the 21st century and could distort the predicted trend. For instance, the current analyses are restricted to the seasonal period of maximum fire activity (May–July). The fire seasons in the boreal forest have been shown to shift to later season burns in recent years (Kasischke and Turetsky 2006) and future fire regime shifts are expected to occur under a warming climate. Furthermore, effects of forest composition (coniferous vs. hardwood) and age structure on fuel availability and moisture regimes, which are important determinants of fire activity under a given climate (Hély et al. 2001), are not accounted for in the current simulations (these limitations also apply to the work done by Flannigan et al. [2005] and Bergeron et al. [2004, 2006]). Changes in fire regimes could lead to shifts in vegetation composition and structure that could provide feedback on the fire activity. Other factors that may be worth attention include changes in the frequency of small precipitation events and their impacts on fine fuels, changes in wind velocity and their impacts on fire behaviour (Li et al. 2000), changes in ignition agents (lightning frequency and human-caused ignition [Price and Rind 1994, Wotton et al. 2003]), changes in land use (e.g., fragmentation of landscapes), interactions with other natural disturbance agents such as insect outbreaks and diseases, feedbacks to the climate system through increases in trace gas emissions (Gillett et al. 2004), and alteration of surface energy exchanges (Chambers and Chapin 2002). The low RE statistic obtained in the FireOcc calibration–verification scheme (Table 1) could partly reflect the confounding influence of one or many of these factors. Some of these weaknesses could partly be addressed by using multiple types of proxies for inferring past fire activity, namely high-resolution fire charcoals found in lake and bog sediments (Carcaillet et al. 2001, Marlon et al. 2006) and

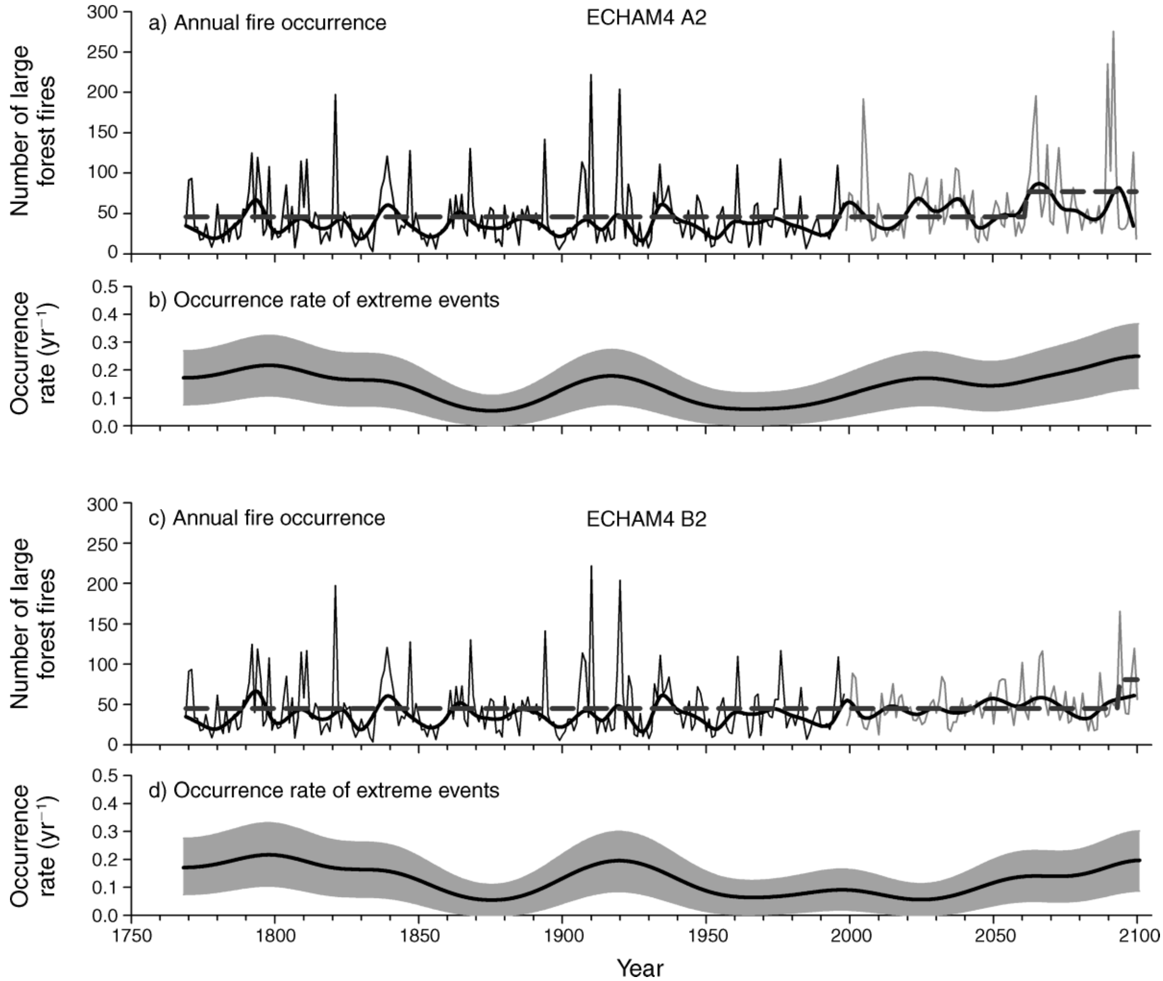

FIG. 6. (a, c) Fire occurrence (n = number of large fire events) as predicted from tree-ring-based drought reconstructions (period 1769–1998) and simulated data from the ECHAM4 model (1999–2100) along with a 10-year median smoothing (thick black line). The time series (light lines) were analyzed using ramp regression (Mudelsee 2000) to determine long-term trend (dashed lines). (b, d) Occurrence rate of extreme fire years. The extreme events were detected using median smoothing (median smoothing parameter k = 100 and a distance to the median threshold of $z = 2.5$; see Mudelsee [2006] for details). The extreme events were further analyzed using a Gaussian kernel, a bandwidth of $h = 15$ years, and bootstrap simulations ($n_{sim} = 10\,000$). The bandwidth was determined using a cross-validation criterion (Mudelsee et al. 2004: Eq. 5). This yielded occurrence rate (bold line) and 90% confidence bands (shaded area). A sensitivity analysis, in which the parameters k, z, and h were varied around the used values, confirmed the robustness of the result.

fire scars and stand-establishment records obtained from dendrochronological dating (Larsen 1997, Bergeron et al. 2001). A calibration on an ensemble of fire proxy data would more efficiently capture the interactions among the various factors listed above. Conversely, simulations of future fire conditions using dynamic climate-vegetation models (de Groot et al. 2003, Keane et al. 2004) would be relevant in attempting to account for changes in lightning probability, vegetation, and fuel types in a changing climate regime.

Conclusion

Boreal forests have disturbance-based dynamics. In the advent of climate change, shifts in vegetation composition and structure triggered by changes in fire regimes could lead to several ecological, economic, and industrial concerns (Weber and Flannigan 1997, Flannigan et al. 2005). Silvicultural management inspired by historical or natural disturbance dynamics, for instance, will have to adapt to potential changes in the abundance of pioneer species, mature to overmature forests, and in species composition (de Groot et al. 2003). Adaptation refers to a variety of responses aimed at reducing adverse impacts or at taking advantage of opportunities created by novel conditions related to climate change (McCarthy et al. 2001, Le Goff et al. 2005).

While the progress in characterizing the spatial and temporal variability of current fire regimes is significant,

TABLE 2. Typical number of large forest fires per year (median FireOcc, in bold) for ~40-yr intervals predicted from tree-ring-based drought reconstructions and the ECHAM4 and CGCM3 global climate models (periods 2047–2065 and 2082–2100 combined).

Period (years)	Model and scenario	Median [10th, 90th]	*n*
1781–1820	tree rings	**35** [16, 108]	40
1821–1860	tree rings	**32** [10, 90]	40
1861–1900	tree rings	**37** [12, 68]	40
1901–1940	tree rings	**36** [14, 104]	40
1941–1980	tree rings	**36** [14, 64]	40
2047–2100	ECHAM4 A2	**47** [25, 134]	38
2047–2100	ECHAM4 B2	**51** [25, 86]	38
2047–2100	CGCM3 A2	**67** [24, 187]	38
2047–2100	CGCM3 A1B	**55** [27, 111]	38
2047–2100	CGCM3 B1	**49** [27, 85]	38

Notes: Numbers in brackets indicate 10th and 90th percentiles. Abbreviations A2, A1B, B1, and B2 denote the four scenarios of projected changes in CO_2 emissions. The number of years used to compute the statistics is represented by *n*. For details, see *Data and methods: Simulated drought data*.

the information is based upon observational data and limited to periods not exceeding a few decades. In some situations this may be problematic: forest composition and structure may rise from climatic conditions and ecological processes spreading over periods of 30 years and going beyond 500 years (see Bergeron et al. 2001, Girardin et al. 2006*a*). For some Canadian regions, fire statistic recording truly began during the second half of the 20th century (i.e., well after the advent of ecological processes that shaped the territory as we see it today). While over short time periods we may understand fire regimes very well, the true amplitude of fire activity may only be provided by paleoclimatological and -ecological records. Such records provide historical contexts with which current regimes can be compared. Additionally, these records may significantly contribute to addressing the impacts of climate change on boreal forests by allowing a comparison of current and future disturbance conditions with an estimated historical range (Flannigan et al. 2001, Bergeron et al. 2004).

In this paper, we addressed three potential sources of discrepancies in studies projecting the likely impacts of climate change on Canadian boreal wildfire activity, namely the reference period with which simulations were compared, the scenario of future greenhouse gases, and the global climate models under use. The prospect of human-caused climate change in the boreal forest is usually associated with increased drought severity and fire activity (Flannigan and Van Wagner 1991, Flannigan et al. 1998, 2005, Stocks et al. 1998, Wotton et al. 2003, Bergeron et al. 2006). Our results for the southern Canadian Boreal Shield forest (Figs. 3 and 4) are in agreement with these studies, no matter which scenario of greenhouse gas emissions is considered. Storylines of greater global economic development (Fig. 2) are typically associated with greater increases in drought severity and fire occurrence (Fig. 5).

In regard to the question of whether or not future fire occurrence will exceed the historical range, results are more ambiguous. In storylines of rapid global economic growth (intense forcing; Fig. 2), the results suggest high probabilities of having future levels reach the upper limit of the historical range (Figs. 6 and 7; Table 2). In storylines of intermediate level of global economic development (Fig. 2), future fire occurrence remains within the range of the past 240 years. It can hence be

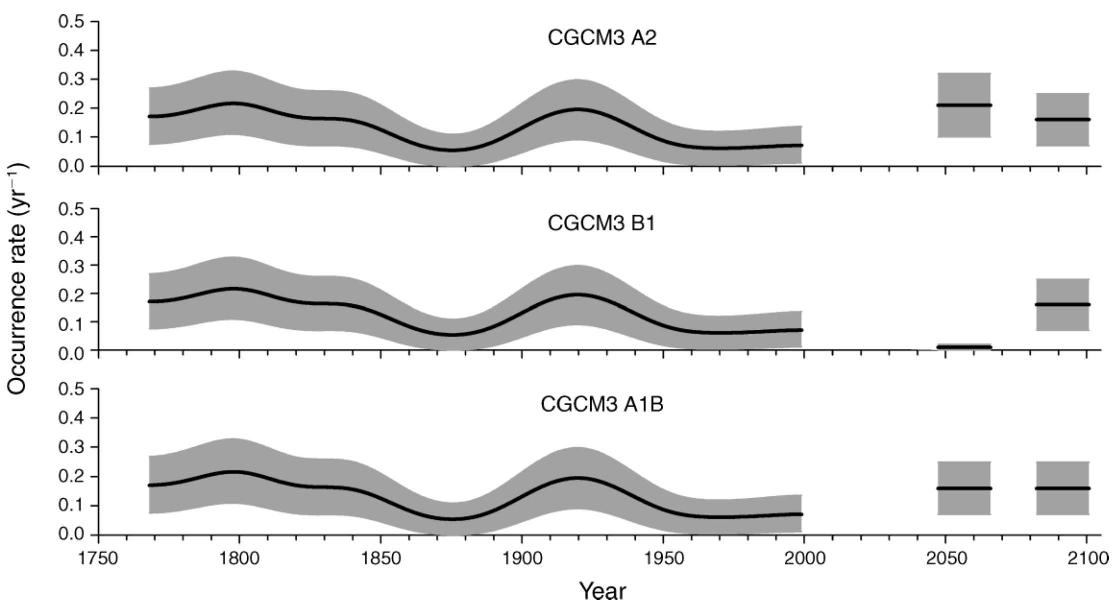

FIG. 7. Occurrence rate of extreme fire years as predicted from tree-ring-based drought reconstructions (period 1769–1998) and simulated data from the CGCM3 model (2047–2065 and 2081–2100). Presentation is as for Fig. 6b, d; for time series of FireOcc estimates, refer to Appendix E.

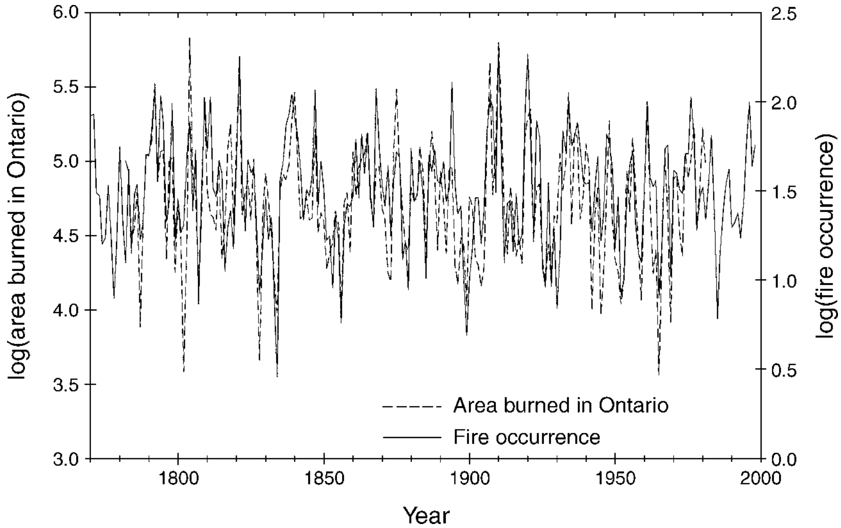

FIG. 8. Comparison between statistical estimates of log-transformed fire occurrence (data from Fig. 4) and log-transformed area burned in Ontario (period 1781–1982, originally measured in hectares; data are from Girardin et al. [2006*a*]). The Pearson correlation *r* between the two is 0.725 ($P < 0.001$); note that the two time series are not statistically independent of each other as both were calibrated on partially overlapping tree-ring chronologies.

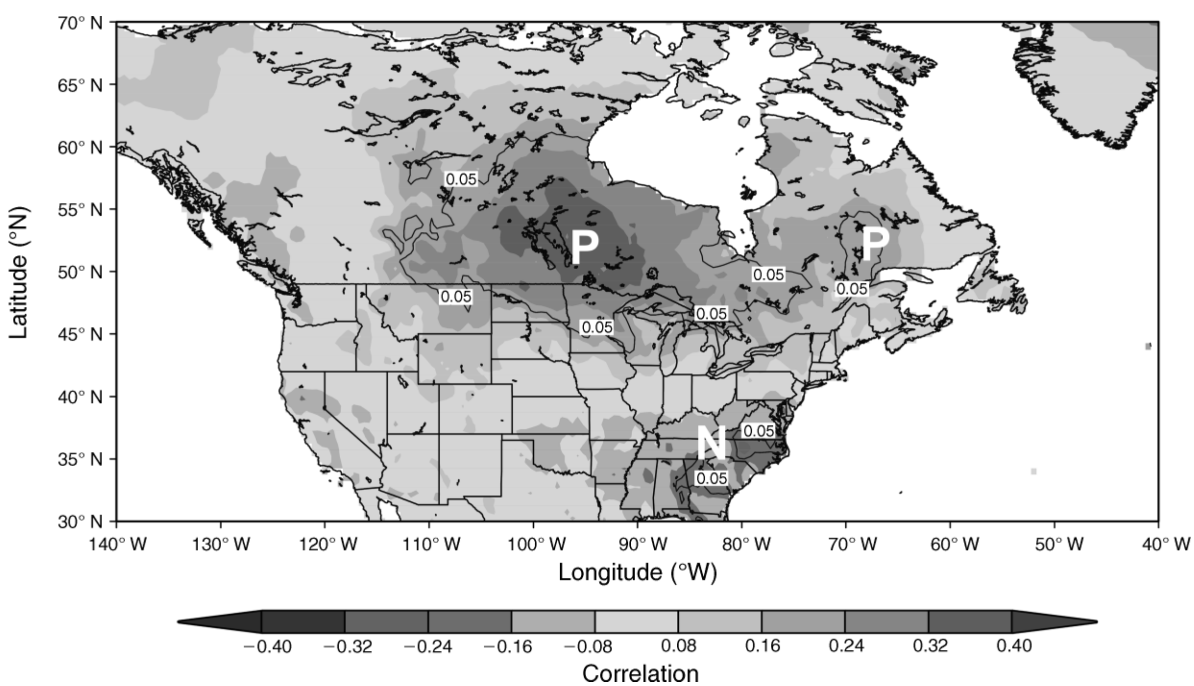

FIG. 9. Correlation between fire occurrence (FireOcc) estimates and seasonal averages of May–July Climate Research Unit (CRU) TS 2.1 global land temperatures (Mitchell and Jones 2005), with 5% significance level (contour line). The CRU TS 2.1 data are interpolated to a 0.5° latitude × 0.5° longitude grid. The period of analysis is 1901–1998. Correlation values between estimates and temperatures at each grid point were used to create the spatial correlation map. The letters P and N refer to positive and negative correlation, respectively. Results show a center of high positive correlation between temperature and FireOcc estimates over western boreal Ontario and northeastern boreal Manitoba and a belt of weaker correlation from Saskatchewan to northeastern boreal Quebec. Results are similar to those obtained from FireOcc observations over the interval 1959–1998. Data were ranked and detrended prior to analysis. The correlation map was created using the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer ⟨http://climexp.knmi.nl/⟩.

concluded that the reference period and scenario of future greenhouse gases are sensitive parameters to the rejection or not of the null hypothesis of "no significant change in wildfire activity."

That said, although in some of our simulations fire occurrence is not expected to be catastrophically different from the past, it is still expected to be above the long-term average (Fig. 6). This is not without consequences for forests, forestry activities, community protection, and carbon budgets, all of which are intimately tied to the fire activity (Chen et al. 2002, Bergeron et al. 2004, 2006, Le Goff and Sirois 2004, Goetz et al. 2005, Coursolle et al. 2006, Balshi et al. 2007). Increases in fire occurrence could notably lead to dramatic increases in wildfire management costs, offset the effects of increasing temperature and atmospheric CO_2 on forest and tree productivity (Goetz et al. 2005), and affect the availability of harvestable trees (Johnston and Williamson 2005). Specifically on the latter aspect, over regions located west of our study area, increases in fire activity as projected in this study could negatively affect the implementation of silvicultural management inspired by historical or natural disturbance dynamics (Bergeron et al. 2004, 2006; see *Introduction*). According to our results, conceivable management options in the next century will likely have to be directed toward minimizing the adverse impacts of increasing fire activity, notably through increased fire suppression, salvage logging, and regeneration enhancement (Le Goff et al. 2005).

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APPENDIX A

A map showing the ECHAM4 and CGCM3 domains (*Ecological Archives* A018-011-A1).

APPENDIX B

Drought Code records covering 1768–2100 (*Ecological Archives* A018-011-A2).

APPENDIX C

Description of the reduction of error and product means tests (*Ecological Archives* A018-011-A3).

APPENDIX D

Sensitivity analyses of Eq. 1 to input variables (*Ecological Archives* A018-011-A4).

APPENDIX E

Fire occurrence estimates obtained from CGCM3 simulations (*Ecological Archives* A018-011-A5).

SUPPLEMENT

Files containing the reconstructions of the July monthly averages of the daily Drought Code covering the period 1768–1998, the CGCM3 and ECHAM4 simulations, the FireOcc data (observations and estimates), and the RAMPFIT software (*Ecological Archives* A018-011-S1).