Temporal variability in area burned for the province of Ontario, Canada, during the past 200 years inferred from tree rings

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Received 25 October 2005; revised 27 April 2006; accepted 16 May 2006; published 9 September 2006.

[1] Area burned variability in the province of Ontario, Canada, was inferred from 25 tree ring width chronologies covering A.D. 1781–1982 and distributed largely across the Boreal Shield. The area burned estimates account for 39.5% of the variance in the actual area burned recorded from 1917 to 1981 and were verified using a split sample calibration-verification scheme. The reconstruction showed that a positive trend in area burned from circa 1970–1981 was preceded by three decades during which area burned was amongst the lowest during the past 200 years. The area burned exhibited a trend toward increasing variance during the past century, recently reaching magnitudes similar to those seen prior to 1850. Signal analyses further identified the presence of two prominent periodic components in area burned that related to decade-to-decade variations. This will help to place the recent increase in area burned in a context relative to the long-term history of the province.

Citation: Girardin, M. P., J. Tardif, and M. D. Flannigan (2006), Temporal variability in area burned for the province of Ontario, Canada, during the past 200 years inferred from tree rings, *J. Geophys. Res.*, *111*, D17108, doi:10.1029/2005JD006815.

1. Introduction

[2] Fire is one of the major disturbances in the forests of the province of Ontario, Canada [*Parker et al.*, 2000]. It is mainly responsible for the spatial and temporal variations of the forest mosaic and has been an integral ecological process since the arrival of vegetation on the landscape. Fire has also been recognized as a significant source of greenhouse gas emissions into the atmosphere [*Amiro et al.*, 2001]. Most of this is in the form of carbon dioxide (CO_2), but quantities of carbon monoxide, methane, long-chain hydrocarbons, and carbon particulate matter are also emitted. From 1989–1996, forest fires constituted about 2% of Ontario's total CO_2 emissions [*Colombo et al.*, 1998].

[3] Fire activity is strongly influenced by four factors – weather/climate, fuels, ignition agents and human activities [*Johnson*, 1992; *Swetnam*, 1993]. Climate is dynamic because of changes in the Earth's orbital parameters, solar output and atmospheric composition. Recently, global climate has been warming as a result of increases of radiatively active gases (carbon dioxide, methane, etc.) in the atmosphere primarily caused by human activities [*Intergovernmental Panel on Climate Change*, 2001]. Human-induced climate change could lead to an increase in forest fire activity in Ontario, owing to the increased frequency and severity of drought years, increased climatic variability and incidence of extreme climatic events, and increased spring and fall temperatures [*Colombo et al.*, 1998; *Parker et al.*, 2000; *Wotton et al.*, 2003; *Gillett et al.*, 2004; *Flannigan et al.*, 2005]. Climate change therefore could cause longer fire seasons [*Wotton and Flannigan*, 1993], with greater fire activity and greater incidence of extreme fire activity years [*Colombo et al.*, 1998; *Parker et al.*, 2000].

[4] Already the warming trend in Canadian temperature [*Karoly and Wu*, 2005] has had a detectable influence on fire activity [*Gillett et al.*, 2004]. Analyses of forest fire data from Canadian agencies indicate an increase in total annual area burned in Canada that matches the summer warming [*Gillett et al.*, 2004]. At the provincial level, area burned in Ontario has also increased since circa 1970 [*Podur et al.*, 2002]. However, whether the Ontario area burned trend results from climate change, increased weather variability, or some other factor is difficult to assess. There is no clear evidence that increases in fire activity in this province reflect a detectable influence of climatic change [*Girardin et al.*, 2004a; *Amiro et al.*, 2004]. Several factors can influence fire activity, including fuel characteristics, land use, topography, fragmentation of the landscape, fire site accessibility, simultaneous fires and fire suppression priorities and policies [*Podur et al.*, 2002]. It is also possible that the provincial fire statistics (number and size of fires) were underreported prior to the 1960s [*Podur et al.*, 2002; *Amiro et al.*, 2004].

[5] This bias in fire statistics [*Podur et al.*, 2002] highlights the complexity of estimating and predicting the effect of climate change on fire activity at the provincial scale. Alternatively, carefully selected proxy data (e.g., tree rings,

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postfire stand age distribution maps, charcoals) can be used to evaluate the long-term behavior of fire variability and provide input for estimating future fire activity [*Carcaillet et al.*, 2001; *Bergeron et al.*, 2004a; *Girardin et al.*, 2006a]. Proxy data also provide quantitative means for measuring the long-term climate control on fire activity [*Bergeron and Archambault*, 1993; *Carcaillet et al.*, 2001]. The impact of future warming on fire activity could be significant and insights gained from looking at the historical relationships between climate and fire could assist the forest sector in developing adaptation plans for climate change.

[6] In this paper we infer past area burned in the province of Ontario using tree ring data. Tree ring chronologies are regressed against area burned data and transfer functions are used to estimate annual area burned at times during which there were no instrumental data. This methodology is commonly employed in climate reconstructions [e.g., *Cook and Kairiukstis*, 1990; *Cook et al.*, 1994; *Fritts*, 2001; *D'Arrigo et al.*, 2003] and has been applied in the western United States and on the Boreal Shield to infer past fire activity using climate proxies [*Westerling and Swetnam*, 2003; *Girardin et al.*, 2006a]. The tree ring model is verified using several measures of common variance between observed and predicted data. Time-dependent trends in estimated area burned mean and variance are analyzed and detection of periodic signals is conducted.

2. Data and Analyses

2.1. Study Area

[7] The province of Ontario (Figure 1) covers a broad zone that extends across the Boreal Shield and the Hudson Plains ecozones. It has a strong continental climate characterized by long cold winters and short warm summers [*Ecological Stratification Working Group*, 1996]. Mean winter temperature (December–February) ranges between −14.5°C in the northwest and −12.0°C in the northeast and −2.8°C in the southeast. Mean summer temperatures (June–August) generally range between 14.0°C in the northwest and 21.5°C in the southeast. Mean annual precipitation ranges from 450 mm in the northwest to 1000 mm in some parts of the east. The Great Lakes have a moderating effect on the climates of central Ontario, warming them in winter and cooling them in summer [*Ecological Stratification Working Group*, 1996]. It is in the northwest boreal region of the province of Ontario that greatest area burned occurs. This is due to a combination of fire-prone ecosystems, more extreme fire weather (a continental climate), and frequent lightning activity [*Stocks et al.*, 2002].

2.2. Fire Data

[8] Annual area burned data for the province of Ontario was used as predictand. The data were obtained from *Podur et al.* [2002] and were initially provided to the authors by *Ontario Ministry of Natural Resources* [1986, also Fire database, unpublished manuscript, 2000]. Information for all documented fires that occurred in the province of Ontario were compiled by the authors and a time series of annual area burned (expressed in ha) covering the 1917–1999 period was created. For the purpose of this study, the *Podur et al.* [2002] area burned data was updated to 2003 using fire statistics from the Ontario Ministry of Natural

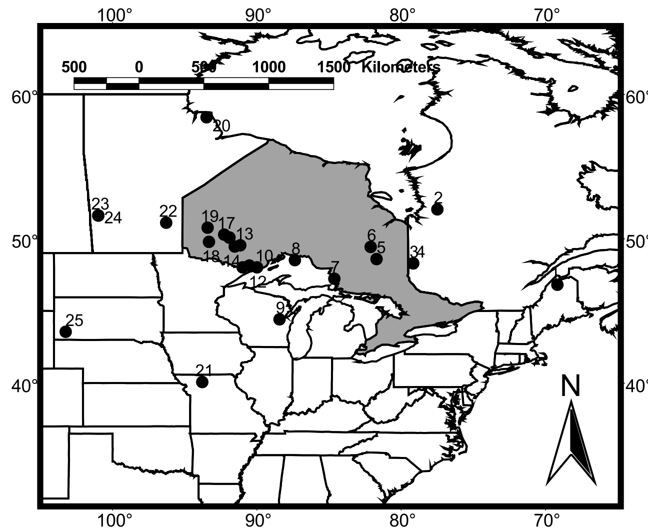

Figure 1. Map showing the location of the province of Ontario (shaded) and the distribution of the 25 tree ring width chronologies (dots). Dots may represent more than one site chronology. Refer to Table 1 for identification of chronologies.

Resources (http://affm.mnr.gov.on.ca). A Shapiro-Wilk test indicated right skewness [*Zar*, 1999] in the annual area burned frequency distributions ($p < 0.001$). The logarithmic transformation (LOG) was found to provide an adequate data transformation to meet the normality assumption ($p = 0.232$).

2.3. Tree Ring Data

[9] A set of AR modeled residual tree ring width chronologies that demonstrated a significant correlation with the province of Ontario area burned was first identified. Pearson correlation analysis was used to screen the area burned record against 90 candidate predictor chronologies from *Girardin et al.* [2006b] and *Contributors of the International Tree-Ring Data Bank* [2004]. The 90 candidate predictors consisted of a set of residual tree ring width chronologies covering the minimum interval 1781–1982 and distributed across the rectangular grid 101°W to 61°W and 41°N to 61°N. Chronologies located outside the provincial limits were included in the analysis since weather systems associated with extreme fire years can cover vast land areas [*Skinner et al.*, 1999]. The period 1781–1982 was chosen to maximize the length of the period of analysis, the number of chronologies in each region, and subsignal strength (used to define a portion of a given chronology with a strong common signal). All are exactly dated chronologies and those covering the portion of the Boreal Shield were, for the majority, sensitive to spring temperature and summer drought [*Graumlich*, 1993; *Girardin et al.*, 2006b]. Earlier spring can favor radial growth, but warm temperatures persisting through June in conjunction with low precipitation can counteract the earlier effect. In summer, optimal assimilation of carbohydrates and tree growth occurs if soil moisture is sufficient to maintain foliage water potential and minimize vapor pressure deficits [*Bonan*, 2002; *Girardin and Tardif*, 2005]. *Tardif and*

Table 1. Sources of the Residual Tree Ring Width Chronologies

	Species	Contributors	Location	Long[a]	Lat[a]	Period	Mean[b]	N[c]	SSS[d]	Sens[e]	r^f	PC1[g]
1	*Thuja occidentalis*	E. R. Cook	Sag Pond	69.20	46.80	1674–1986	246	23	1703	0.15	−0.21	0.28
2	*Picea mariana*	F. Schweingruber	Eastmain River	77.51	52.02	1739–1988	164	27	1804	0.16	−0.20	0.44
3	*Thuja occidentalis*	J. Tardif	Lac Duparquet	79.19	48.28	1417–1987	302	43	1570	0.16	−0.24	0.34
4	*Thuja occidentalis*	S. Archambault	Lac Duparquet	79.19	48.28	1186–1987	507	46	1285	0.14	−0.22	0.42
5	*Pinus resinosa*	M. P. Girardin	Blue Lake	81.72	48.58	1606–2002	223	46	1776	0.19	−0.22	0.54
6	*Picea mariana*	M. P. Girardin	René-Brunelle Provincial Park	82.13	49.42	1721–2002	148	50	1790	0.13	−0.26	0.45
7	*Pinus resinosa*	M. P. Girardin	Montreal River	84.65	47.22	1773–2003	158	37	1781	0.28	−0.25	0.45
8	*Betula papyrifera*	M. P. Girardin	Rainbow Fall Provincial Park	87.38	48.50	1766–2001	143	48	1783	0.33	−0.23	0.30
9	*Pinus resinosa*	D. L. Koop and H. D. Grissino-Mayer	Hartwick Pines State Park	88.45	44.40	1770–1987	202	52	1777	0.18	−0.21	0.48
10	*Pinus resinosa*	L. J. Graumlich	Saganaga Lake	90.00	48.00	1719–1988	188	43	1780	0.23	−0.40	0.63
11	*Pinus resinosa*	L. J. Graumlich	Saganaga Lake	90.54	48.13	1644–1988	201	51	1691	0.26	−0.47	0.60
12	*Pinus resinosa*	C. W. Stockton	Ed Shave Lake	91.00	48.00	1700–1982	162	38	1798	0.24	−0.39	0.65
13	*Pînus resinosa*	M. P. Girardin	Sowden Lake	91.17	49.53	1640–2001	216	40	1738	0.15	−0.33	0.66
14	*Pinus strobus*	M. P. Girardin	Lake Sandbar Provincial Park	91.55	49.45	1773–2002	104	54	1902	0.18	−0.25	0.59
15	*Pinus resinosa*	M. P. Girardin	Sioux Lookout Provincial Park	91.92	50.07	1772–2001	134	44	1822	0.24	−0.48	0.58
16	*Pinus resinosa*	M. P. Girardin	Sioux Lookout	91.92	50.07	1766–2002	116	29	1807	0.18	−0.33	0.57
17	*Thuja occidentalis*	M. P. Girardin	Lake Seul south	92.28	50.27	1762–2002	110	42	1874	0.17	−0.30	0.50
18	*Pinus strobus*	M. P. Girardin	Eagle Lake	93.33	49.77	1712–2002	126	40	1762	0.22	−0.27	0.57
19	*Pinus resinosa*	M. P. Girardin	Lake Packwash Provincial Park	93.43	50.75	1744–2002	168	38	1830	0.20	−0.33	0.67
20	*Larix laricina*	J. Tardif	Churchill	93.50	58.40	1721–2000	125	71	1780	0.24	0.23	−0.16
21	*Quercus alba*	D. N. Duvick	Nine Eagles State Park	93.80	40.06	1672–1982	134	27	1858	0.25	−0.30	0.35
22	*Pinus resinosa*	J. Tardif	Black Island	96.30	51.10	1709–2001	102	148	1722	0.15	−0.21	0.42
23	*Picea glauca*	J. Tardif	Duck Mountain Provincial Forest	101.00	51.60	1776–2001	129	81	1828	0.18	−0.38	0.44
24	*Picea mariana*	J. Tardif	Duck Mountain Provincial Forest	101.00	51.60	1758–2001	177	64	1795	0.13	−0.34	0.38
25	*Pinus ponderosa*	D. Meko and C. H. Sieg	Reno Gulch	103.26	43.54	1281–1991	282	32	1595	0.24	−0.38	0.31

[a]Lat is latitude and Long is longitude, in degrees.
[b]Mean is mean length of measurement series.
[c]N is sample depth of tree ring series.
[d]SSS is subsample signal strength and is used to define the portion of the residual chronology (year y to present) with a strong common signal [*Wigley et al.*, 1984]. Most chronologies show sufficient replication to estimate the signal of a chronology with greater sample size for an interval covering the early 19th century to present.
[e]Sens is mean sensitivity of the residual chronology.
[f]Pearson r between a given chronology and the area burned time series over 1917–1981 ($p < 0.05$ when $-0.24 > r > 0.24$; $n = 63$).
[g]Chronologies loading on the first principal component (PC1), which accounted for 23.9% of the variance in the tree ring data set.

Bergeron [1997] and *Girardin et al.* [2004b, 2006b] provided evidence of statistical association between radial growth of many of the tree species used for this study and the Canadian Drought Code (CDC), which is used daily across Canada to monitor fire danger [*Van Wagner*, 1987]. The CDC is an indicator of seasonal drought effects on the amount of moisture in the deep forest floor.

[10] Age/size-related trends and disturbance effects contained in the raw ring width measurement series were removed using cubic smoothing splines of 66% of the ring width series length with 50% frequency response [*Cook and Peters*, 1981]. Autocorrelation in the tree ring data was removed using autoregressive modeling [*Cook and Holmes*, 1986] since autocorrelation in the fire data was nonsignificant (AR[1] = 0.19, $p = 0.115$). Biweight robust means of the residual series were computed to create residual tree ring width chronologies. All chronologies were constructed using ARSTAN [*Holmes*, 1999].

[11] The correlation screening revealed a subset of 25 chronologies (Figure 1 and Table 1) out of the original 90 that correlated significantly ($-0.20 > r > 0.20$; $p < 0.10$) with the area burned record over a common period from 1917 to 1982. These 25 chronologies were retained for inclusion in the area burned reconstruction model.

2.4. Reconstruction of Area Burned

[12] The 25 chronologies, held together on a common interval 1781–1982, were transformed into principal components (PCs) to remove multicollinearity [*Legendre and Legendre*, 1998]. A correlation matrix was used so that all descriptors could contribute equally to the clustering of objects, independently of the variance exhibited by each one. Four PCs, with eigenvalues >1.4 and accounting for 46.7% of the total variance, were retained for subsequent analyses. To account for lagged effects of climate on tree growth [e.g., *Graumlich*, 1993; *Girardin and Tardif*, 2005; *Girardin et al.*, 2006b] and on the fire season [*Van Wagner*, 1987], the PCs were lagged backward and forward by one year and also included in subsequent analyses. The program used for the principal component analysis was CANOCO 4.0 [*ter Braak and Smilauer*, 1998].

[13] A stepwise multiple regression employing a backward selection was used to calibrate the PCs (12 predictors: present, backward and forward lags) against the LOG-scaled area burned data (period 1917–1981). The stability of the regression model was tested using a split sample calibration-verification scheme. Two subcalibrations of the period 1917–1949 and 1950–1981 were conducted using the selected predictors. The strength of the relationship between the reconstruction and observations over the independent verification periods 1950–1981 and 1917–1949, respectively, was measured by the reduction of error (RE), sign test, and the product means test (PM) discussed by *Cook et al.* [1994] and *Cook and Kairiukstis* [1990]. The RE provides a sensitive measure of reconstruction reliability. Whenever RE is greater than zero the reconstruction is considered as being a better estimate of instrumental data (LOG-scaled area burned) than the calibration period mean. A significant sign test result indicates good fidelity in the direction of year-to-year change in the instrumental and reconstructed data. A significant PM test result indicates that the magnitude and the direction of these changes are statistically significant. The program used for the stepwise multiple regression analyses was SYSTAT 9.1 [*Systat*, 1998]. The program used for calculation of the RE and PM verification statistics was VFY [*Holmes*, 1999].

2.5. Signal Analyses

[14] A Continuous Wavelet Transform (CWT) analysis was conducted to identify nonstationary periodic signals in the area burned reconstruction. CWT was used to decompose signals into wavelets, small oscillations that are highly localized in time [*Torrence and Compo*, 1998]. Whereas the Fourier transform decomposes a signal into infinite length sines and cosines, effectively losing all time localization information, the CWT basis functions are scaled and shifted versions of the time-localized mother wavelet. The CWT is used to construct a time-frequency representation (spectrum) of a signal that offers very good time and frequency localization. The CWT analysis was conducted using the nonorthogonal Morlet wavelet basis with a wave number of 6. The 95% confidence limit was drawn from the distribution of points in the spectrum [*Torrence and Compo*, 1998]. In addition, Singular Spectrum Analysis (SSA), a robust data-adaptive method of extracting signals from noise in time series, was conducted [*Elsner and Tsonis*, 1996]. The SSA is an eigendecomposition filtration that sets a signal strength threshold for retaining all signal-bearing eigenmodes and filtering out all noise-containing ones.

[15] To verify that signals identified in the reconstruction were consistent with instrumental ones, squared wavelet coherency [*Torrence and Webster*, 1999; *Grinsted et al.*, 2004] was conducted between the instrumental and reconstructed data over their common interval 1917–1981. The wavelet coherency exposes regions of two CWTs with high common power and further reveals information about the phase relationship. The statistical significance level of the wavelet coherence against red noise backgrounds was estimated using Monte Carlo methods. CWT was conducted using the Matlab software provided by *Torrence and Compo* [1998]. SSA was conducted using the program AutoSignal version 1.5 [*AISN Software*, 1999]. Wavelet coherence was conducted using the Matlab software package WTC-R9 provided by *Grinsted et al.* [2004]. All signal analyses were done on LOG-scaled area burned data.

3. Results

3.1. Tree Ring Model

[16] The stepwise regression model indicated that 39.5% of the variance in the LOG-scaled annual area burned in the province of Ontario was accounted for by the leading principal component (PC1) of the 25 residual tree ring width chronologies (Figure 2). The model's equation

$$[\mathrm{E1}]\, Y_{\mathrm{LOG}t} = 4.723 - 0.365\,\mathrm{PC1}_t - 0.196\,\mathrm{PC1}_{t-1}$$

indicated that while the present year radial growth component $\mathrm{PC1}_t$ accounted for the largest amount of variation in area burned in the province of Ontario, part of the variance could also be explained by the radial growth component of the previous year $\mathrm{PC1}_{t-1}$. This relation likely reflects the influence on area burned of a winter carryover of soil moisture content from summer of the year_{t-1} to year_t. Exceptional fire years for instance may occur when there is an insufficient amount of snow to recharge the soil layer in spring.

[17] Verification statistics of the strength of the subcalibration models are shown in Table 2. These statistics indicate significant predictive skills of the area burned reconstruction. Positive RE and significant correlation coefficients indicate tendencies for the area burned reconstruction to reproduce with confidence both high (Figure 2a) and relatively low frequency (Figure 2b) variations in actual data. The PM and sign tests both indicate significant predictive skills of the area burned reconstruction to reproduce the magnitude and direction of year-to-year changes.

[18] In Figure 3, the LOG-scaled area burned data was back transformed to arithmetic units using the exponential (EXP) function described by *Baskerville* [1972]. As is generally the case with tree ring reconstructions, the LOG-scaled estimated area burned data exhibited lower variance than the actual data, and hence the EXP-scaled reconstruction tended to underestimate extreme fire years. Episodes of succeeding years of large area burned were estimated approximately at 1790–1794, 1803–1807, 1818–1822, 1838–1841, 1906–1912, 1920–1921, and 1933–1936 (Figure 3, based on standard deviations of smoothed reconstructions >1.0). The tree ring model revealed the year 1804 as the year of most extreme area burned. During this single year, area burned equaled 14.5% of the total area burned (5.71M ha) estimated during 1917–1981. In instrumental area burned, this single year would represent an approximate 1.2M ha (if weighted against the 8.44M ha actual area burned during 1917–1981). Years 1910 (13.4%), 1821 (10.5%), 1907 (9.8%), 1792 (7.2%) and 1875 (6.5%) were, among others, also estimated as years of extreme area burned.

[19] For identification of long-term trends in estimated area burned, the mean and variance were analyzed using a sliding window of 25 years on the LOG-scaled data. Differences in the mean area burned were confirmed using the permutation *t*-test (*n* replications = 100,000); differences in variance were confirmed using the *F* test. The sliding window analysis showed higher mean area burned values

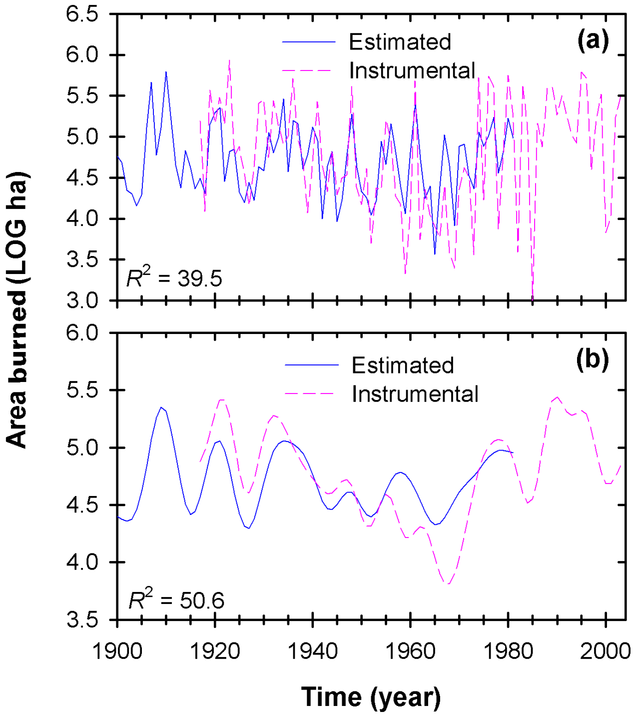

Figure 2. (a) Instrumental (dashed line) and estimated (solid line) LOG-scaled area burned in the province of Ontario. (b) 10-year window polynomial curves (order 8) of Figure 2a. R^2 shows the amount of variance explained by the tree ring model over the 1917–1981 calibration period.

prior to 1840 and through the 1860s–1880s and the 1910s–1920s (Figure 4a). Mean values during the mid-20th century were the lowest in the record. A *t*-test revealed that the mean area burned in the 1940–1969 period was significantly lower than that of 1910–1939 (t = 2.19, p = 0.031). The analysis of variance (Figure 4b) showed high variance values in the pre-1850 period and a peak of high variance values during the 1900s–1920s. The analysis also showed a trend toward higher variance values through the 20th century. An *F*-test indicated that the variance value of the 1900–1981 period was significantly higher than those of 1840–1899 (p = 0.035). The variance values of the 1782–1839 period were also significantly higher than those of 1840–1899 (p = 0.033). Variance at the beginning of the former period may be affected by lower sample replication (Table 1). Overall, these analyses demonstrate that while the mean area burned was lower during recent decades, year-to-year variations of area burned around this mean have been moderately greater than 100–150 years ago.

Table 2. Calibration and Verification Statistics of the Province of Ontario LOG-Scaled Area Burned Reconstruction

Calibration Period	1917–1981	1917–1949	1950–1981
R square	0.395	0.268	0.525
Standard error	0.521	0.441	0.514
First-order autocorrelation	0.043	−0.046	−0.202
Durbin-Watson D statistic	1.880	2.031	2.382
Verification Period	–	1950–1981	1917–1949
Correlation[a]	–	0.723	0.517
RE[b]	–	0.349	0.231
PM[c]	–	4.095	3.463
Sign test[d]	47/18	24/8	24/9

[a]Significant at $p < 0.05$ if $r > 0.30$.
[b]Considered satisfactory if RE > 0. Whenever RE is greater than zero, the reconstruction is considered as being a better estimate of area burned than the calibration period mean.
[c]Considered significant at $p < 0.05$ if PM > 1.70. A significant PM test result indicates that the magnitude and the direction of year-to-year changes are statistically significant.
[d]Agreement/disagreement: $p < 0.05$ if sign test ≥23/9. For the calibration of 1917–1981, $p = 0.001$ if sign test = 47/18. A significant sign test result indicates good fidelity in the direction of year-to-year changes in the real and reconstructed data.

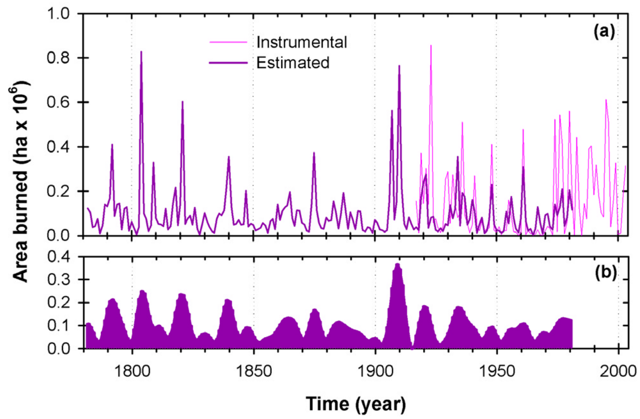

Figure 3. (a) Reconstruction of area burned in the province of Ontario for 1782–1981 (thick line). Thin line represents instrumental data (1917–2003). (b) 10-year window polynomial curve (order 8).

3.2. Signal Analyses

[20] An analysis of time-dependent periodicities of the LOG-scaled area burned reconstruction was conducted

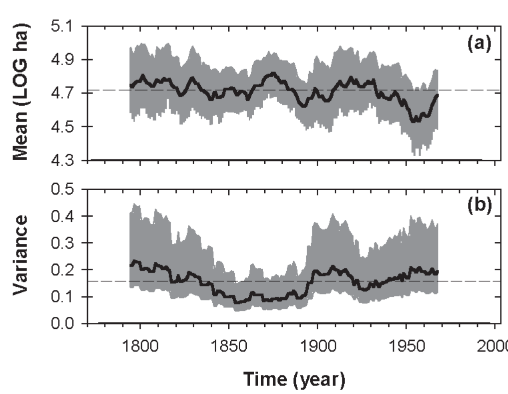

Figure 4. 25-year overlapping sliding window (thick line) of (a) mean and (b) variance with 95% confidence levels (shaded area) of LOG-scaled area burned (window central value is shown). Dashed line represents values calculated over the 1782–1981 period.

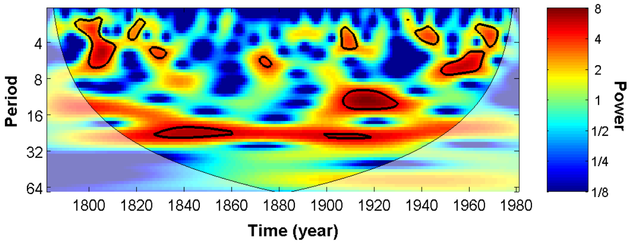

Figure 5. Continuous wavelet transformation (CWT) power spectra of LOG-scaled area burned. Dark red indicates areas of large power in time and period scales; thick contour is the 5% significance level for red noise (AR[1] = 0.30). The lighter shade delineates the cone of influence where zero padding has reduced the variance.

(Figure 5). The CWT spectrum indicated areas of strong power in the 17–32 years/cycle band. In addition, the spectrum showed significant power in the 9–16 years/cycle band and also intermittent 2–8 years/cycle signals. These signals were particularly present during the 20th century. One can also note the concordance between long-term trends in reconstruction (Figure 3) and amplitude changes in the 9–32 years/cycle band (Figure 5). Though not significant and within the cone of influence, the reconstruction also showed greater power in the 32–64 years/cycle band during the 20th century. The squared wavelet coherence indicated that areas of large power in the estimated CWT during the interval 1917–1981 were consistent with those in the actual CWT (Figure 6). Furthermore, areas with significant common power showed in-phase behavior (arrows pointing to the right), an indication of a positive correlation between the actual and estimated area burned data in all time and period scales.

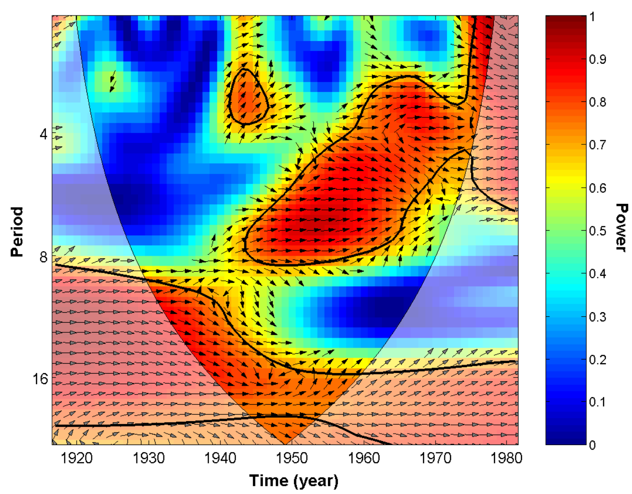

Figure 6. Squared wavelet coherence between the normalized estimated and instrumental area burned data over their common interval 1917–1981. Areas of large common power in time and period scales between estimated and actual data are shown in red. The 5% significance level against red noise is shown as a thick contour. The lighter shade delineates the cone of influence where zero padding has reduced the variance. The relative phase relationship is shown as arrows, with in-phase pointing right, antiphase pointing left, actual area burned leading estimated area burned by −90° (−1/4λ) pointing up, and estimated area burned leading actual area burned by 90° (1/4λ) pointing down. In-phase and antiphase relationships may be interpreted as positive and negative correlation, respectively, in time and period scales.

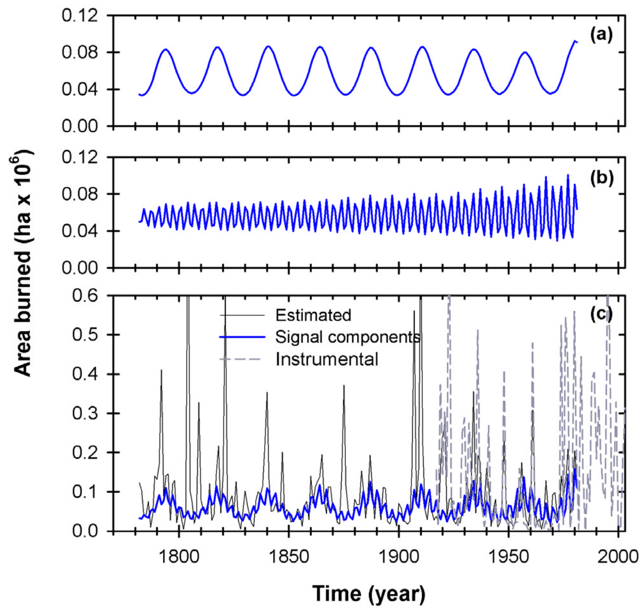

Figure 7. Retained signal components with periodicities of (a) 22.2 and (b) 3.3 years/cycle (thick solid line) and (c) estimated and instrumental data (thin solid line and dashed line, respectively). Analyses were done on LOG-scaled data; results were back transformed to arithmetic units.

[21] The SSA of the area burned reconstruction revealed the presence of two prominent signals that were consistent with those detected by CWT analysis. The first signal was from the 22.2 years/cycle and accounted for 13.5% of the variance in the reconstruction (Figure 7a). This signal component generally showed a good fit with the reconstruction; the signal components explained many of the decade-to-decade changes in area burned. The second signal was from the 3.3 years/cycle and accounted for 12.2% of the variance (Figure 7b). This signal showed increasing amplitude since approximately 1850. Overall, the signal components (Figure 7c) accounted for 24.2% of the variance in the reconstruction. A permuted Pearson correlation analysis (with n replications = 100,000) further indicated a significant relationship between the combined signal components and the actual area burned record during the common interval 1917 to 1981 (r = 0.346, p = 0.005).

4. Discussion

4.1. Tree Ring Model Performance

[22] The results showed that tree ring width chronologies could provide reliable indicators of area burned at the

provincial scale. The tree ring model was verified over independent periods using several measurements of common variance. This covariance may be explained by the fact that both ecological processes are primarily responding to similar environmental delivery factors, that is, the presence of upper atmospheric ridges and troughs upstream or above the study area [*Skinner et al.*, 1999; *Girardin and Tardif*, 2005]. Most of the area burned in the boreal forest is attributed to large persistent blocking high-atmospheric pressure systems that cause dry fuel conditions and winds over large land areas [*Newark*, 1975; *Johnson and Wowchuk*, 1993; *Bessie and Johnson*, 1995; *Skinner et al.*, 1999]. Though humans during the past decades have been an important source of fire ignition [*Stocks et al.*, 2002], these conditions are major contributors to the large stand-renewing fires [e.g., *Johnson et al.*, 1990; *Masters*, 1990; *Johnson*, 1992]. In Ontario, area burned was associated with two patterns of ridging anomalies, one located over the forested areas of Saskatchewan, Manitoba, and northwestern Ontario and the second southwest of Hudson Bay [*Skinner et al.*, 1999]. Trees also respond to similar environmental signals. Large persistent blocking high-atmospheric pressure systems that cause dry fuel conditions also lead to increases in water deficits in trees, and hence to reductions of tree radial growth [*Garfin*, 1998; *Girardin and Tardif*, 2005]. Our results therefore support earlier findings by *Larsen and MacDonald* [1995] who suggested that tree ring width could be used to infer past fire activity, under the condition that both processes were responding to summer dryness and seasonal distribution of precipitation.

[23] Interestingly, the strong covariance between area burned and tree growth occurs in spite of noise in the fire and tree ring data. Many serious problems can occur with provincial fire statistics primarily because of inconsistent and expanding detection systems [*Murphy et al.*, 2000]. The quality of forest fire statistics varies over both time and space; the size of the protected area, the area that was effectively under fire management, is an increasing function of time [*Podur et al.*, 2002]. Given the high levels of common variance, we can assume that this bias is minimal in records from the province of Ontario during the period 1917–1981. One should, however, be careful when interpreting the reconstruction. Extrapolation of the findings to the recent area burned records (1982 to present) should be done cautiously. Part of the increases in area burned can be attributed to the inclusion of new reporting areas [see *Podur et al.*, 2002]. Also, regions of greater fire incidence and tree ring data replication (e.g., northwest boreal region) are likely to be weighted accordingly in the reconstruction. Therefore the reconstruction is most likely representative of area burned temporal variability within these areas. The reconstruction may also underestimate or omit variability and temporal changes in conditions leading to spring and late summer fires. In Canada, 78% of the area burned from 1959 to 1998 occurred in June and July, while 8% occurred during May and 13% during August [*Stocks et al.*, 2002]. Finally, the area burned reconstruction contains little information relative to centennial-long changes. The tree ring width chronologies were detrended to remove growth trends (section 2.3), such that mainly annual to multidecadal scale variance was retained.

4.2. Area Burned Variability and the Climate Systems

[24] The reconstruction indicated that the most recent increase in area burned in the province of Ontario (circa 1970–1981) [*Podur et al.*, 2002] was preceded by the period of lowest fire activity ever estimated for the past 200 years (1940s–1960s). Given the high covariance between the tree ring model and the actual record, we can attribute much of the increase (up to 1981) to variability in the climate systems. However, while in recent decades (circa 1970–1981) area burned has increased, it remained below the level recorded prior to 1850 and particularly below levels recorded in the 1910s and 1920s (Figure 3). In addition, the reconstruction indicated that variance has changed during the past century toward greater year-to-year variations. The variance in the recent decades, nonetheless, was similar to that recorded prior to 1850. The CWT and SSA analyses also showed time-dependent changes in the frequency domain, that is, an increase in the amplitude of high-frequency signals.

[25] Numerous studies of forest stand age distributions across the Canadian boreal forest report lower fire activity since circa 1850 [*Masters*, 1990; *Johnson and Larsen*, 1991; *Larsen*, 1997; *Bergeron et al.*, 2001, 2004a, 2004b; *Tardif*, 2004]. Extreme fire activity in the 1910s and 1920s across eastern Canada was also reported [*Bergeron et al.*, 2001, 2004a]. These fires were large stand replacing fires and likely involved extreme dryness of forest fuels. Reconstruction of the Canadian Drought Code across the southern limit of the Boreal Shield indicated the occurrence of several decades of drier conditions than average during the pre-1850s and early 20th century [*Girardin et al.*, 2004b, 2006b]. In part, these fires may have been the result of a settlement period in tandem with dry weather [*Lefort et al.*, 2003], but these episodes are well highlighted in the smoothed area burned reconstruction presented in this study (Figure 3b). These apparent similarities between studies confirm that the area burned reconstruction provides insights on aspects related to the 'natural' behavior of the fire regimes, namely on annual to multidecadal scale variance, the occurrence rate of extreme events [see *Girardin et al.*, 2006a] and the presence of periodicities in fire activity.

[26] Periodicities are prominent features of climate systems. The most recognized ones include a persistent 50–100 year NH climate signal observed in proxy data of large-scale temperature variability [*Mann et al.*, 1995; *D'Arrigo et al.*, 2003]. Some modeling evidence supports the hypothesis of a solar-driven signal on this timescale [*Shindell et al.*, 2001; *Waple et al.*, 2002]. Others however indicate that the 50–100-year NH signal could be generated from internal coupled ocean-atmosphere variability alone [*Delworth and Mann*, 2000]. Similar modeling results were reported regarding a ~20-year signal in the North Pacific region. Anomalies in the central and eastern North Pacific Ocean associated with this signal can be generated by combining SST anomalies in the equatorial Pacific with stochastic feedback from the atmosphere [*Schneider et al.*, 2002; *Newman et al.*, 2003; *Wu and Liu*, 2003]. This North Pacific mode affects climate across large regions of the Boreal Shield [*Girardin et al.*, 2004a, 2004b, 2006b]. The

22 years/cycle signal detected in the area burned reconstruction could be related to this mode, although wavelet coherency analyses tend to show nonstationary behavior in the relationship [*Girardin et al.*, 2004b]. Another prominent signal is the 11 years/cycle that may relate to solar effects on the behavior of the Arctic upper atmosphere circulation mode [*Shindell et al.*, 2001]. Anomalies in the lower NH stratospheric polar vortex affect the momentum of the upper troposphere's polar longitudinal winds and induce a mean meridional circulation that can extend to the Earth's surface [*Thompson et al.*, 2002]. Finally, most consistent in the Atlantic region are peaks at 2.5, 5–6, 8, and about 64 years/cycle [*Wanner et al.*, 2001].

[27] Because the behavior of the climate systems could change because of anthropogenic effects, area burned in the province of Ontario during the 21st century could behave differently than observed during the warming of the last 150 years. Several ocean-atmosphere circulation models suggest that increasing levels of greenhouse gases have the potential to alter natural variations in ocean-atmosphere circulation modes [e.g., *Wanner et al.*, 2001; *Bigg et al.*, 2003; *Boer et al.*, 2004]. The importance of the periodic components and the occurrence rate of extreme events, for instance, could be lowered or increased. Research has suggested that the frequency and persistence of blocking ridges in the upper atmosphere will increase in an enhanced CO_2 climate [*Lupo et al.*, 1997; *Meehl and Tebaldi*, 2004]. Given that area burned is closely tied to the occurrence and persistence of blocking ridges [*Skinner et al.*, 1999], one should expect greater area burned in a changing climate. Other uncertainties also arise from the possibility that future warming over Canada may not be compensated for by an increase in precipitation in all regions [*Flannigan et al.*, 2005], as was generally the case during the past 150 years. Longer fire seasons and more ignitions may also be contributors to increases in future area burned [*Price and Rind*, 1994; *Wotton and Flannigan*, 1993; *Wotton et al.*, 2003].

[28] However, the anticipated increase in area burned should be placed in a historical context much longer than that provided by the observational area burned record (Figure 3b). When considering the long-term history as a reference period (say the last 200–300 years), some simulation models indicate that, for many regions of the boreal forest, area burned will be lower than experienced 150 years or so ago [*Bergeron et al.*, 2004a]. The validation of this finding may have strong implications for the development of boreal forest management strategies inspired by natural disturbance regimes (discussed by *Bergeron et al.* [2004a]). *Girardin et al.* [2006a], notably, reported that forest stand age distributions are not solely a function of the average fire activity, but a function of the interval between periods of clustered extreme fire years such as seen prior to 1850. Perhaps when discussing potential impacts of climate change, different aspects of fire activity should be considered, that is, aspects related to the mean, the periodicities, the variance, and/or the occurrence rate of extreme area burned events.

5. Conclusion

[29] This study showed the potential of tree rings for reconstruction of past area burned at the provincial scale at times during which there was no instrumental record. Such studies can help to place the recent observed increase in fire activity in a context relative to the long-term history of the province. The reconstruction for the province of Ontario showed that the positive trend in area burned from circa 1970–1981 was preceded by three decades during which area burned was amongst the lowest during the past 200 years. Given the high covariance between the tree ring model and the instrumental record, we can attribute many of these variations to variability in the climate systems. With the increasing number of tree ring data networks and increasing quality of fire data, it is conceivable that this study could be repeated at other locations throughout Canada.

[30] **Acknowledgments.** We thank Justin Podur and the Aviation and Forest Fire Management Branch of the province of Ontario for providing the province of Ontario area burned data. We also thank Aslak Grinsted for providing the WTC-R9 software package used in the wavelet coherency analysis. We acknowledge the Sustainable Forest Management Network (SFMN) and the Natural Sciences and Engineering Research Council of Canada (NSERC) for funding this research. We thank the three anonymous reviewers for providing helpful comments on an earlier version of the manuscript and Pamela Cheers for her editing work.

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