Global Change Biology

Global Change Biology (2009) **15**, 2751–2769, doi: 10.1111/j.1365-2486.2009.01869.x

Heterogeneous response of circumboreal wildfire risk to climate change since the early 1900s

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Abstract

We investigated changes in wildfire risk over the 1901–2002 (AD) period with an analysis of broad-scale patterns of July monthly drought code (MDC) variability on 28 forested ecoregions of the North American and Eurasian continents. The MDC is an estimate of the net effect of changes in evapotranspiration and precipitation on cumulative moisture depletion in soils, and is well correlated with annual fire statistics across the circumboreal (explaining 25–61% of the variance in regional area burned). We used linear trend and regime shift analyses to investigate (multi-) decadal changes in MDC and percentage area affected by drought, and kernel function for analysis of temporal changes in the occurrence rates of extreme drought years. Our analyses did not reveal widespread patterns of linear increases in dryness through time as a response to rising Northern Hemisphere land temperatures. Instead, we found heterogeneous patterns of drought severity changes that were inherent to the nonuniformly distributed impacts of climate change on dryness. Notably, significant trends toward increasing summer moisture in southeastern and southwestern boreal Canada were detected. The diminishing wildfire risk in these regions is coherent with widely reported decreases in area burned since about 1850, as reconstructed by dendrochronological dating of forest stands. Conversely, we found evidence for increasing percentage area affected by extreme droughts in Eurasia (+0.57% per decade; $P<0.05$) and occurrence rates of extreme drought years in Eurasian taiga (centered principally on the Okhotsk–Manchurian taiga, $P=0.07$). Although not statistically significant, temporal changes in occurrence rates are sufficiently important spatially to be paid further attention. The absence of a linear trend in MDC severity, in conjunction with the presence of an increase in the occurrence rate of extreme drought years, suggest that fire disturbance regimes in the Eurasian taiga could be shifting toward being increasingly pulse dependent.

Keywords: area burned, climate change, drought code, evapotranspiration, extreme, fire, forest, kernel function

Received 16 October 2008 and accepted 15 December 2008

Introduction

Forest fire is a major driver of the global carbon cycle and atmospheric chemistry, and is a significant contributor to terrestrial ecosystem functioning and to biodiversity (Burns & Honkala, 1990; Amiro *et al*., 2001; McRae *et al*., 2001; Bond *et al*., 2005). Recent extreme forest fire years across North America and Eurasia have raised awareness of potential human-caused effects on this disturbance agent. Notably, the activity of large

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fires increased strikingly in the mid-1980s in the western United States (Westerling *et al*., 2006), northwestern Canada (Stocks *et al*., 2003; Gillett *et al*., 2004; Kasischke & Turetsky, 2006; Girardin, 2007), and northeastern Quebec (Le Goff *et al*., 2007), and, at the end of the 20th century, in Russia (Conard *et al*., 2002). Human-caused climate change has often been viewed as a major contributor to this upward trend, among other factors. Understanding the linkages between forest fire, its cause and economic consequences is of fundamental importance in developing strategies for its management (Holmes *et al*., 2008).

The influence of climate on forest fire involves tradeoffs between the amount of available fuel and fuel flammability (Pausas, 2004; Westerling, in press). In boreal forests, dry forest fuels and winds are recognized as being the major contributors to large-stand replacing fires (final size >200 ha). These fires spread rapidly when the fuels are dry and the weather conditions are warm, dry and windy. Episodic droughts conducive to such fires last 10 days or more, and are driven by blocking high-pressure systems above or upstream from the affected regions, causing air subsidence, warming and drying over areas sometimes spanning over 1000 km (Skinner *et al*., 1999). On seasonal to interannual time scales, the average and variability of these climatic conditions determine the flammability of forest fuels and the fire behavior (Girardin, 2007; Macias Fauria & Johnson, 2008; Westerling, in press). As opposed to arid, sparsely vegetated ecosystems, fuel is generally not considered a limiting factor for fire spread in the boreal forest (Johnson & Larsen, 1991; Westerling, in press). This is primarily because fine fuels in closed-canopy boreal forests are relatively constant after canopy closure at 15 or 20 years.

In boreal forests, climate change may act upon fuels through increased evapotranspiration not compensated for by increasing precipitation, or increased frequency of extreme drought years due to more persistent and frequent blocking high-pressure systems (Gillett *et al*., 2004; Meehl & Tebaldi, 2004; Groisman *et al*., 2007; Girardin & Mudelsee, 2008). Earlier snow melt and longer summer droughts with climate change could also expose forests to higher wildfire risk, although this effect remains to be validated (Wotton *et al*., 2003; Kasischke & Turetsky, 2006; Westerling *et al*., 2006; Westerling, in press). Adding to these influences, several other factors are not to be neglected in inducing changes in fire activity, namely increasing land use and human ignition (Drobyshev *et al*., 2004; Mouillot & Field, 2005; Achard *et al*., 2008; Granström & Niklasson, 2008; Marlon *et al*., 2008), impacts of forest management practices (Westerling *et al*., 2006), episodic shifts in drought regimes due to oceanic forcing (Girardin *et al*., 2004a; Macias Fauria & Johnson, 2008), or, at longer time scales, orbital and solar forcing upon the global climate (Carcaillet & Richard, 2000; Power *et al*., 2008).

Some contradictory evidence in the literature has led authors to question the likelihood of seeing an increase in boreal wildfire risk under warming of the Northern Hemisphere (Bergeron & Archambault, 1993; Macias Fauria & Johnson, 2008). Despite warming since about 1850 (Trenberth *et al*., 2007) and increased incidence of large forest fires in the 1980s, a number of studies indicated a decrease in boreal fire activity in the last 150 years or so (e.g. Masters, 1990; Johnson & Larsen, 1991; Larsen, 1997; Lehtonen & Kolström, 2000; Bergeron *et al*., 2001, 2004a, b; Mouillot & Field, 2005). This holds true for boreal southeastern Canada, British Columbia, northwestern Canada and Russia. In eastern Canada, for instance, the average time for an area to burn completely has shifted from 124 years before 1920 to 360 years afterward (also see Bergeron *et al*., 2004b, 2006 for reviews). In the southern Rockies of British Columbia, Masters (1990) reported the onset of longer fire cycles around 1928 (the fire cycle length constitutes the time required to burn an area equal to the area of interest). In Wood Buffalo National Park, Alberta, Larsen (1997) reported the onset of a longer fire cycle around 1860. A number of causes have been suggested for the diminishing fire activity, including effectiveness of fire suppression (Mouillot & Field, 2005; Marlon *et al*., 2008), changes in land use and landscape fragmentation (Lefort *et al*., 2003; Marlon *et al*., 2008), or changes in oceanic/atmospheric circulation regimes (Girardin *et al*., 2004a; Le Goff *et al*., 2007). However, the spatial extent for these long-term changes is large enough to suggest that climate is likely to have played a key role in their induction. The fact that diminishing fire activity has also been detected on lake islands on which fire suppression has never been conducted provides another argument in support of climate control (Bergeron, 1991).

There is no consensus on the relative importance of climate change since the early 1900s on driving changes in wildfire risk in circumboreal forests. A primary reason is the lack of long-term, annually resolved fire statistics from unmanaged/undisturbed forests. Fire statistics are biased by several temporal changes, namely in land use, fire detection and reporting, area under protection, methodological approaches for determining fire perimeters, increasing effectiveness of fire suppression, and types of ignition (human vs. lightning-caused fires), and are largely restricted to the late 20th century (Dixon & Krankina, 1993; Kasischke *et al*., 2002; Podur *et al*., 2002; Stocks *et al*., 2003; Goldammer *et al*., 2007). The use of wildfire risk (or fire danger) indices provides an alternative to fire statistics. In a study over Eurasia using four types of wildfire risk indices, Groisman *et al*. (2007) concluded that significant changes in potential forest fire risk have taken place over northern regions during the past century. No significant changes were found over northern Europe (Groisman *et al*., 2007). The performance of various wildfire risk indices differed only in small details. In Canada, analyses of wildfire risk using components of the fire weather index (FWI) system by Amiro *et al*. (2004) over 1959−1999 also did not reveal widespread changes in wildfire risk during the second half of the 20th century. Conversely, Girardin & Wotton (in press) found significant decreases in drought severity in western and eastern Canada when analyzing the 1901–2002 period. The reference period could be a critical aspect to consider when evaluating changes in wildfire risk according to Girardin & Mudelsee (2008). Additionally, the evaluation of seasonal extremes vs. average fire conditions also appears critical as suggested by studies by Lefort *et al*. (2004) and Lauzon *et al*. (2007).

In this paper, we investigate changes in wildfire risk over the 1901−2002 period with an analysis of broad-scale patterns of drought variability on forested ecoregions of the North American and Eurasian continents. We use an alternative wildfire risk index to that used in Groisman *et al*. (2007) along with advanced statistical modelling, providing an independent evaluation of their earlier findings. Three hypotheses related to wildfire risk response to climate change over 1901−2002 were postulated and statistically tested. These hypotheses were formulated on the basis of the widely accepted evidence that temperatures have been rising in the Northern Hemisphere over 1901−2002 (Trenberth *et al*., 2007) and that fire activity has been increasing during the late 20th century (Stocks *et al*., 2003). The hypotheses and associated predictions are:

(1) Fire activity in boreal forests is significantly correlated with variations in moisture content in deep layers of the forest floor.

(a) Annual area burned (AAB) exhibits a positive correlation with moisture deficits in deep layers of the forest floor.

(2) Wildfire risk is increasing over time throughout circumboreal forests.

(a) The percentage of areas experiencing summer drought is increasing on the North American and Eurasian continents.
(b) Average summer drought severity exhibits a significant positive linear trend in many boreal forests.

(3) Occurrence rate of extreme drought years exhibits an upward trend over time.

(a) The increase in wildfire risk in boreal forests is attributed to more frequent extreme drought years.

Methods

Monthly drought code (MDC)

The net effect of changes in evapotranspiration and precipitation on cumulative moisture depletion in soils is represented in this study by the monthly drought code (MDC). The MDC is a generalized monthly version of the daily drought code (DC) widely used across Canada by forest fire management agencies in their monitoring of wildfire risk. The use of the DC has recently begun in other countries, as methodologies have been developed to electronically gather daily weather data and produce daily maps for large portions of northern Europe and northern Asia (de Groot *et al*., 2007a). In support of Canada's National Forest Carbon Monitoring, Accounting and Reporting System, implementation of the DC in the Carbon Budget Model of the Canadian Forest Sector has also begun (de Groot *et al*., 2007b). The DC is a moisture index upon which many forest practitioners working across the circumboreal area may rely.

The MDC was developed by Girardin & Wotton (in press) to be used in carrying out seasonal drought characterization analyses where daily weather data necessary for computation of the daily DC are not available. The DC, and hence the MDC, represent the moisture content of organic matter that is on average about 18 cm thick and $25\,\mathrm{kg\,m^2}$ dry weight, for a bulk density of $138.9\,\mathrm{kg\,m^{-3}}$. The equation linking the DC to its moisture equivalent (Q; unitless) from Van Wagner & Pickett (1985) is:

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

The 400 constant in Eqn (1) represents the maximum theoretical moisture content of the fuel represented by the DC, which roughly corresponds to the water-holding capacity of the soil, i.e. 100 mm (Van Wagner, 1987). In its daily version, the DC has a response time of 62 days at 15 °C and 44 days at 30 °C. This long response time served as the basis for the development of a monthly approximation model. The MDC formulation may be summarized as follows. First, potential evapotranspiration E (unitless quantity) over month m follows the method of Thornthwaite & Mather (1955) and is given by:

$$E_m = N(0.36(\bar{T}_{mx}) + L_f), \qquad (2)$$

where $\bar{T}_{mx}$ is the monthly mean of daily maximum temperatures (°C), L_f is the standard day length adjustment factor (Van Wagner, 1987), and N is the number of days in the month. Next, computation of the MDC is carried out twice in a month to reduce bias that may arise when the forest floor becomes saturated in the spring. Drying taking place over the first half of the month (DC_{HALF}) is calculated as:

$$DC_{HALF} = MDC_0 + 0.25E_m, \tag{3}$$

where MDC_0 is the MDC from the end of the previous month. Total monthly rainfall (r_m) is simulated to occur in the middle of the month, and the moisture equivalent in the layer after rain Q_{mr} (unitless) is calculated as:

$$Q_{mr} = 800e^{(-DC_{HALF}/400)} + 3.937RM_{EFF}. \tag{4}$$

In these equations, r_m is reduced to an effective rainfall (RM_{EFF}; mm) after canopy and surface fuel interception using $RM_{EFF} = 0.83r_m$. An estimate of the MDC value at the end of the month (MDC_m; unitless), for which total rainfall and mean temperature apply, is calculated as:

$$MDC_m = 400\ln(800/Q_{mr}) + 0.25E_m. \tag{5}$$

Finally, MDC_0 and MDC_m are averaged to find a mean drought value for the month:

$$MDC = (MDC_0 + MDC_m)/2. \tag{6}$$

When calculating the next month's MDC, the value of MDC_m from the previous month then becomes the new MDC_0. For further details on the MDC formulation, one can consult the original publication (Girardin & Wotton, in press).

Girardin & Wotton (in press) found that the MDC generally followed trends in the monthly means of the daily DC closely (r^2 ranging from 0.87 to 0.95 for $n = 612$ sample months). Predictive skills of the MDC were found to be lower in locations characterized by high precipitation regimes (maritime locations), whereas the prediction error was found to be essentially distributed during late spring and early summer months. There are no absolute guidelines as to the meaning of the MDC values but, generally speaking, DC values below 200 are considered low while values around 300 may be considered moderate. A rough rule of thumb used by fire managers across Canada is that a DC rating of 400 or more indicates that fire will involve burning of deep subsurface and heavy fuels. The index generally peaks in mid- to late August, beyond which it either declines or maintains the same value; during extreme years with late season fires, this does not always hold true (McAlpine, 1990; Girardin *et al.*, 2004b). The reversal in August is only attributed to a change in day length, and is not a function of seasonal precipitation.

Climate data

In this application, long-term changes in wildfire risk in North America and Eurasia were evaluated using climate research unit (CRU) total monthly precipitation and monthly average daily maximum temperature data (CRU TS 2.1 data; Mitchell & Jones, 2005) interpolated into a 0.5° latitude by 0.5° longitude grid covering the 1901–2002 period. The MDC was computed at each grid point using the program SIMMDC (Girardin & Wotton, in press). Next, regional averages of the MDC were computed following the Olson *et al*. (2001) classification of World Terrestrial Ecoregions. A total of 28 ecoregions from the Boreal Forests/Taiga and Temperate Broadleaf and Mixed Forests biomes were considered in this study (Fig. 1).

The paucity of climate stations in boreal and taiga forests in the early part of the 20th century (Groisman *et al*., 2007) may cause CRU data to be biased by an excessively smoothed climate record (i.e. one with low variance among years) due to data interpolation. This bias was tested in each regional average of the MDC by analyzing the variance from 1901 to 2002. The MDC records were divided into subperiods 1901–1920 and 1921–2002, and the *F*-test was conducted with the hypothesis H_o that the standard deviations of the two subperiods were equal. H_o was rejected when the significance level P was found to be lower than the critical value of 0.05 (indicating a potential bias originating from data interpolation). Out of the 28 ecoregions, data from two ecoregions were identified as being problematic: the Northern Canadian Shield taiga and Eastern Canadian Shield taiga. Other divides were tested and suggested that two other ecoregions were potentially problematic: East Siberian taiga and Northeast Siberian taiga. This bias was taken into account in our analyses and interpretation of the results.

Statistical analyses

One of the prerequisites for the analysis of the MDC is that it should be used reliably as an approximation of fire-conducive climate variability over broad areas and over time. This implies that seasonal MDC should correlate well with AAB (hypothesis 1). As a means of verification, AAB statistics from seven locations across circumboreal and taiga ecoregions were used in a correlation analysis. Area burned data used are presented in Table 1. Goodness-of-fit with the regional

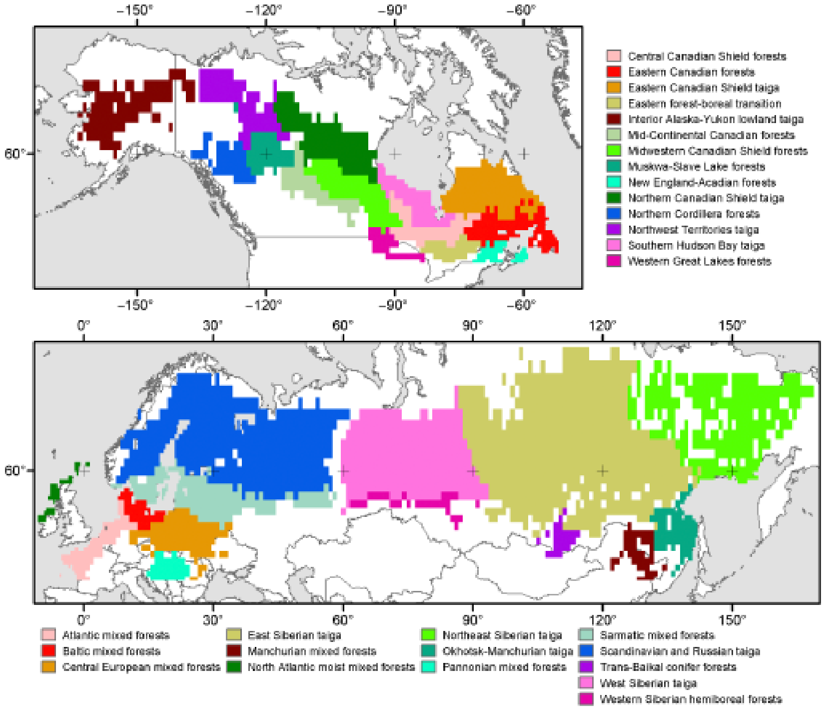

Fig. 1 Map of forested ecoregions under study (Olson *et al.*, 2001).

MDC records was described using the square of the Spearman rank correlation coefficient (r^2; von Storch & Zwiers, 1999). The null hypothesis of no significant relationship between MDC and area burned (hypothesis 1) was rejected when $P < 0.050$. A logarithmic transformation was applied to the area burned data for visual inspection of the interannual variability. The choice of area burned data was guided by the length of records and the literature already existing on potential biases and under reporting at earlier times. Notably, in remote regions of the boreal forest, it can be assumed that undetected fires have burned large areas and, therefore, were unlikely included in early fire statistics (Weber & Stocks, 1998). Although Canadian fire statistics go back to the 1920s, statistics before 1970 are considered incomplete. Conversely, Kasischke *et al.* (2002) pointed out that the quality of fire information present in fire databases may be dependent on the methods used to delineate fire perimeters. Consequently, the quality of fire statistics in Alaska increases from fair during the 1960s to good in the 1980s. Other problems occur, as before 1988 official statistics in Russia were inaccurate (Shvidenko & Goldammer, 2001). Annual data for this country are thus limited to the last decade. Given all these biases, it was expected that, in our analyses, not all of the area burned variance would be explained by variations in the MDC. Furthermore, this study strictly focused on climate factors and did not take into account nonlinear effects and regime shifts that may be triggered by interaction of climatically controlled fire hazards with other nonclimatic factors.

Trends in MDC were examined at three spatial scales: Northern Hemisphere, continental (North America and Eurasia), and regional (28 terrestrial ecoregions). First, percentage of area across the Northern Hemisphere, North America and Eurasia experiencing July drought (defined as any area where July MDC exceeds a given threshold) was computed for each year for the 1901–2002 period. Thresholds for drought severity classes were set to (i) low ($\text{MDC} < 160$), (ii) moderate ($\text{MDC} < 200$), (iii) high ($\text{MDC} < 240$), and (iv) extreme ($\text{MDC} \geq 240$). Long-term changes in the percentage index (hypothesis 2) were detected using regime shift detection on a sliding 30-year window with correction for serial persistence in data (Rodionov, 2006). This analysis allowed us to verify that changes in the mean from one period to another were not just the manifestation of a red noise [i.e. AR(1)] process (probability $\sigma = 0.05$; outliers weight parameter $= 6$; IP4 method for red noise correction). Linear trends in the percentage index were also examined for 1901–2002 using least-squares linear regressions (von Storch & Zwiers, 1999; Zar, 1999). Goodness-of-fit was described by the coefficient of determination (R^2). Significance of the slope was tested against the null hypothesis that the trend

Table 1 Sources of forest fire statistics

Location	Type	Period	Source	Ecoregions used in spatial averages of July MDC	*n* grids
State of Alaska (USA)	Total annual area burned	1950–2003	Kasischke *et al.* (2002)	Interior Alaska-Yukon lowland	369
Northwestern Canada	Annual area burned by fires of size >200 ha (sums of ecoregions 4, 5, 11)	1959–1999	Stocks *et al.* (2003)	Northern Cordillera forests Muskwa-Slave Lake forests Northern Canadian Shield taiga Northwest Territories taiga	992
Province of Ontario (Canada)	Total annual area burned	1917–2002	Podur *et al.* (2002)	Midwestern Canadian Shield forests (east of 100°W) Central Canadian Shield forest Western Great Lakes forests	544
Province of Quebec (Canada)	Total annual area burned	1950–1998	Lefort *et al.* (2004)	Eastern Canadian Shield taiga Central Canadian Shield forest (east of 80°W) Eastern Canadian forests	851
St. Petersburg region (Russia)	Total annual area burned	1966–1999	Federal Forestry Agency (2000)	Scandinavian and Russian taiga (28°E–36°E, 58°N–62°N)	95
Komi Republic (Russia)	Total annual area burned	1950–2000	Drobyshev & Niklasson (2004)	Scandinavian and Russian taiga (40°E–61°E, 57°N–67°N)	642
Russia	Total annual area burned based on ground and aerial observations	1992–2007	Goldammer *et al.* (2007)	Okhotsk–Manchurian taiga East Siberian taiga (120°E–143°E, 45°N–74°N)	884

Ecoregions used in spatial averages of July MDC are also indicated ('*n* grids' refers to the number of grid cells used for each region). MDC, monthly drought code.

was different from zero, using a variant of the *t* test with an estimate of the effective sample size that took into account the presence of serial persistence in data (von Storch & Zwiers, 1999). Next, linear trends in regional records of MDC were examined for 1901–2002 using the statistical test described above, with the exception that MDC data were ranked before analysis to satisfy the assumption of normality of model residuals (Zar, 1999).

Changes in the occurrence rate of years with extreme wildfire risk (hypothesis 3) were analyzed using kernel functions. Extreme wildfire risk was defined as years during which MDC exceeded 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), and is thus well suited for the CRU data used in this study. Kernel estimation allows detailed inspection of time-dependent event occurrence rates and assessment of significant changes with the help of confidence bands. A Gaussian kernel, *K*, was used to weight observed event dates, $T(i)$, $i, \ldots, N$ (total number of events), and calculate the occurrence rate, λ, at time *t* as:

$$\lambda(t) = h^{-1} \sum\nolimits_i K((t - T(i))/h). \qquad (7)$$

The running median smoothing parameter *k* was set to 40 years. In the few cases where changes in the background states were obvious (see 'Climate data'), a more flexible parameter was used (lowest fixed at 25 years). The number of extreme events under analysis was set to approximate the highest 15% percentile (function of the distance to the median *z*, which varies by increments of 0.5). The kernel bandwidth, *h*, was set to 25 years (Mudelsee *et al.*, 2004). Sensitivity analyses, in which parameters *z*, *h* and *k* were varied around the values used, confirmed the robustness of the results. 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 was calculated. This procedure was repeated 10 000 times, and a percentile-*t* confidence band was calculated. The confidence bands helped to assess whether highs and lows in the occurrence of extreme events were significant or not. Detected trends in occurrence rate were confirmed for the measured interval [$t1$; $t2$] using the statistical test u described by Cox & Lewis (1966):

$$u = \frac{\sum_{i=1}^{n} t(i)/n - (t1 + t2)/2}{(t2 - t1)\sqrt{[1/(12n)]}}, \tag{8}$$

where t denotes drought event dates (years) and n is data size. This parametric procedure tests the null hypothesis 'constant occurrence rate' ($u = 0$) against one-sided alternatives such as 'increasing occurrence rate' ($u > 0$) (under H_O, statistic u is standard normally distributed). One seeks to disprove the hypothesis of a constant occurrence rate when the P value is lower than 0.05. Program CALIZA, which supersedes XTREND (Mudelsee, 2002), was used for occurrence rate estimation, and CLIM-X-DETECT (Mudelsee, 2006) was used for detection of extremes.

Results

Hypothesis 1: area burned is significantly correlated to summer MDC

The timelag of the DC, and hence of the MDC, is long enough so that July records integrate the influence of the two previous months, i.e. May and June (see 'Monthly drought code'). Over 82% of AAB (or 76% of all fires of size >200 ha) in Canada from 1959 to 1999 did so during these 3 months (Stocks *et al.*, 2003). Hence, this study focuses entirely on that single month.

As shown in Fig. 2, the July MDC is a good predictor of AAB. In all ecoregions under study, MDC explained about 25–50% of the variance. The lowest correlation was found in northwestern Canada, and was largely due to an upward trend in AAB that did not correspond to an increase in MDC. Indeed, r^2 significantly increased ($r^2 = 0.36$, $P < 0.0001$) with removal of the positive trend in AAB data before correlation analysis. Removal of the trend from the AAB data of the Komi Republic using a second-order polynomial function also led to a significant increase in the amount of shared variance ($r^2 = 0.61$). Recalculation of correlation coefficients for periods during which fire statistics quality was thought to be optimal also significantly increased the amount of shared variance. For instance, AAB in the province of Quebec shared 60% of its variance with that of MDC over the 1972−1998 period (1972 being the onset of systematic fire detection in this province; Lefort *et al.*, 2004). The goodness-of-fit was found to be rather stable over time in Alaska, whereas in Ontario the pattern was reversed. Over the 1917−1970 period, it was 60% of the Ontario AAB variance that was explained by July MDC, whereas over the 1971−2002 period, r^2 diminished to attain 0.32. Visual inspection shows an abrupt discontinuity in the relationship between Ontario AAB and MDC around the late 1960s, particularly in the low frequencies (i.e. an increase in AAB did not correspond to an increase in MDC). This discontinuity in Ontario and the low r^2 in northwestern Canada are not considered as evidence for rejecting hypothesis 1. Instead, they reflect the widely reported bias in fire statistics due to changing fire detection systems and areas under protection over time (see 'Statistical analyses'; Van Wagner, 1987; Podur *et al.*, 2002; Stocks *et al.*, 2003; Drobyshev & Niklasson, 2004). Substitution of Ontario AAB by number of fires in Ontario per year (FireOcc) led to a higher correlation, with 50% of the variance in FireOcc from 1971 to 2002 explained by MDC ($P < 0.0001$). As for Russia, goodness-of-fit with AAB (Fig. 2g) was significant with MDC records from areas where most of the area burned occurred (see Dixon & Krankina 1993, their Table 2), namely the Okhotsk–Manchurian taiga ecoregion (48% of shared variance; $P = 0.0116$) and the southeastern part of the East Siberian taiga ecoregion (41% of shared variance; $P = 0.0353$). Goodness-of-fit over Russia was confirmed using bootstrap analysis to address sample size limitation [95% confidence interval (0.06, 0.88); Mudelsee, 2003].

Hypothesis 2: wildfire risk increased throughout circumboreal forests

The percentage of area experiencing summer drought in the Boreal Forests/Taiga and Temperate Broadleaf and Mixed Forests biomes at circumboreal/continental scales recorded significant (multi-) decadal variations over the 20th century (Fig. 3). At the scale of the Northern Hemisphere, the percentage of area exceeding the lowest drought severity threshold oscillated from $\sim 72\%$ between 1942 and 1988 to $\sim 77\%$ between 1901−1941 and 1989−2002. Such oscillation was not apparent in high drought severity classes. Indeed, indices of high and extreme drought severity classes showed an increase of over 2% in mean percentage of area around 1988, but did not show a reduction in the 1940s.

At the continental scale, North American and Eurasian percentage of area indices showed unsynchronized patterns of short-term changes, and indices were uncorrelated with each other (e.g. for MDC > 200: correlation r over the 1901−2002 period $= -0.065$, $P > 0.200$). This lack of correlation between North American and Eurasian indices occurred at all frequency scales contained in the 2−32 years/cycle band according to a wavelet coherency analysis (results not shown). Some similarities between North America and Eurasia were noticed at longer time scales. A

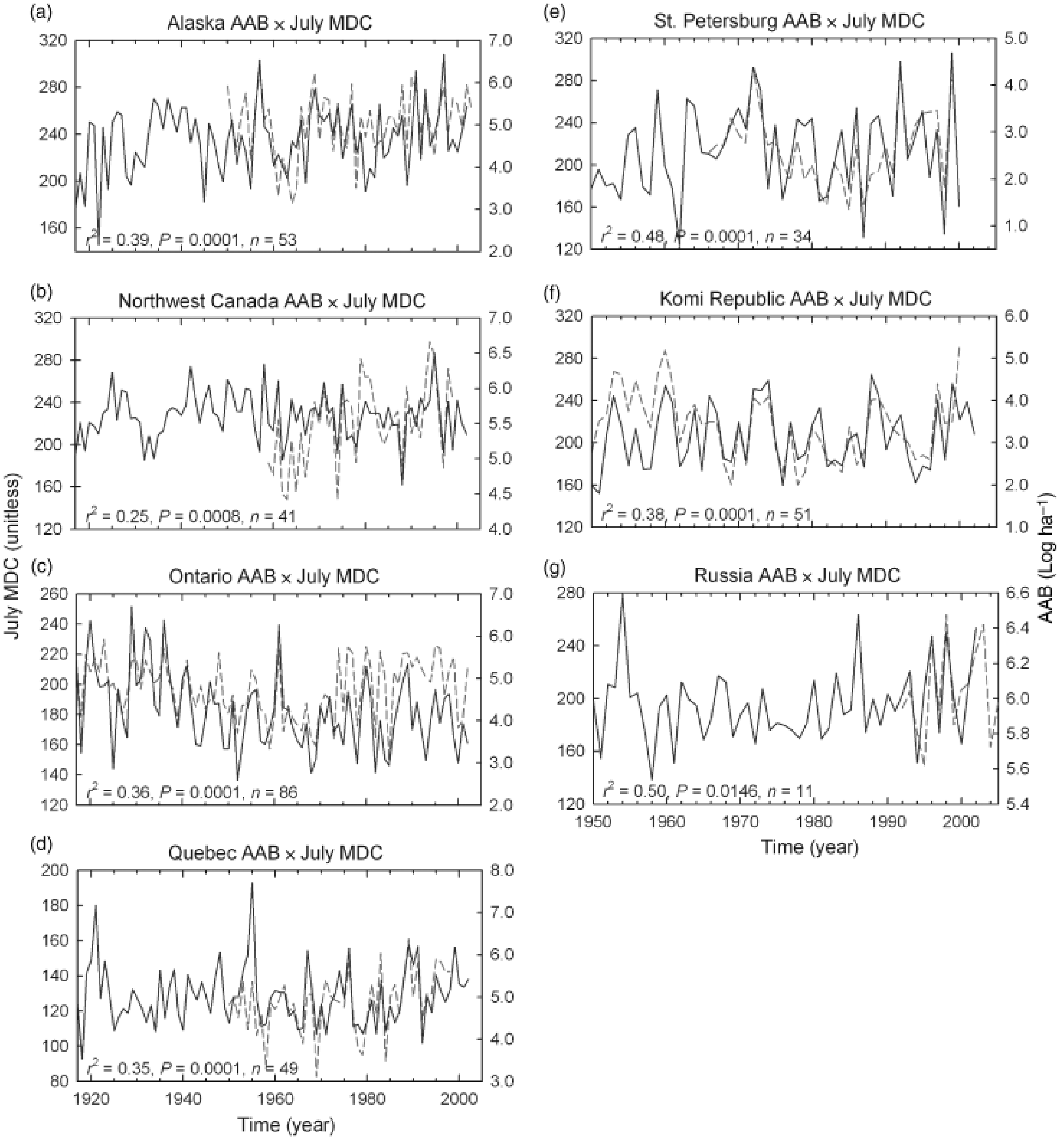

Fig. 2 Regional averages of the July monthly drought code (MDC, solid line) vs. logarithmic-transformed annual area burned (AAB, dashed line) in (a) the state of Alaska, (b) northwestern Canada, (c) the province of Ontario, (d) the province of Quebec, (e) the St. Petersburg region (European Russia), (f) the Komi Republic (European Russia), and (g) Russia. The square of the Spearman rank correlation (r^2) expresses the goodness-of-fit between AAB and July MDC records over their common period. Refer to Table 1 for MDC data sets used and to Supporting Information for locations.

significant reduction in the percentage of area exceeding the MDC = 160 threshold was detected in 1957 for North America and in 1941 for Eurasia (both recorded a reduction of 6%). A reversal toward higher percentage values was also detected for both continents (1989 for North America and 1982 for Eurasia). In regard to higher July MDC thresholds, increases in the percentage of area exceeding 280 MDC units were detected in 1937 for North America (by $<2\%$) and in 1983 for Eurasia (by $<4\%$). Linear trend analysis applied to the indices indicated that the amount of area experiencing extreme drought severity has been expanding over Eurasia in the course of the 20th century ($P<0.05$) (Table 2). This trend was also significant on the Northern Hemisphere

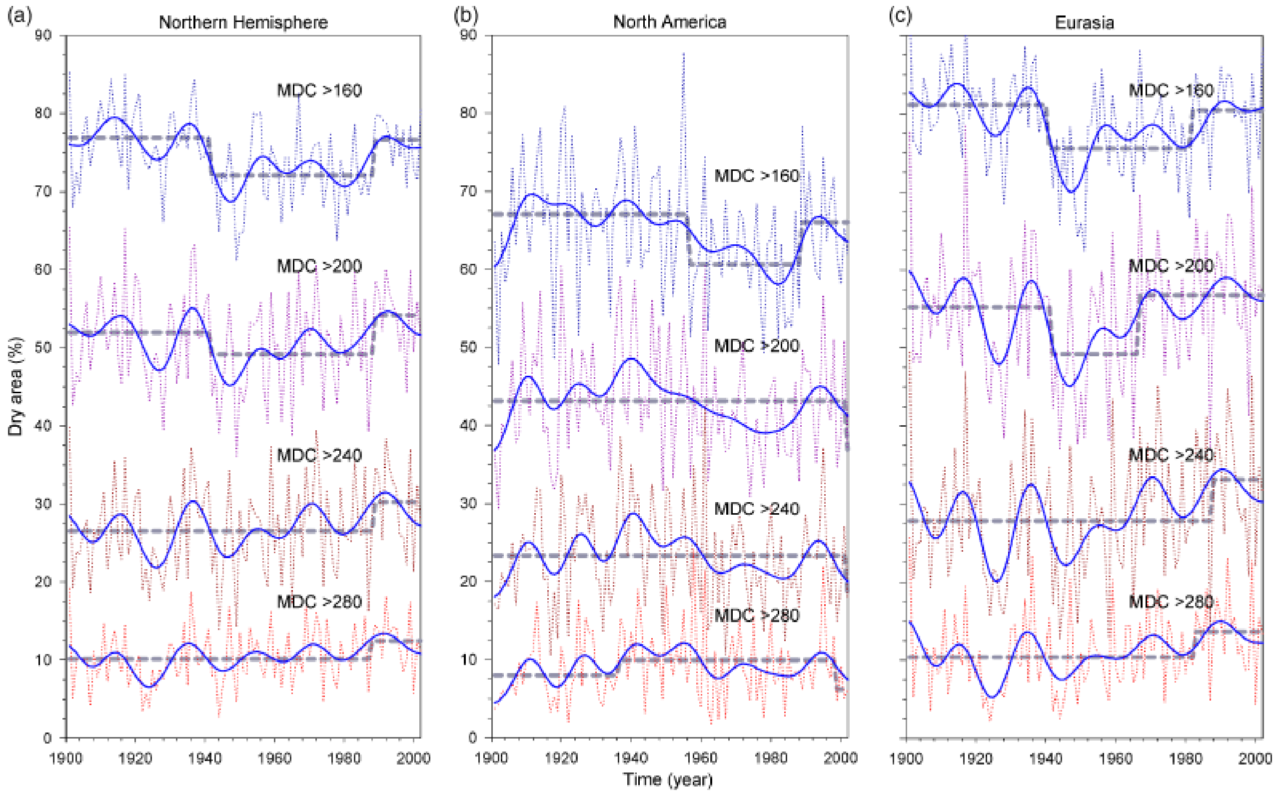

Fig. 3 Percentage of area experiencing low [monthly drought code (MDC) >160] to extreme (MDC >280) July droughts across (a) the Northern Hemisphere, (b) North America, and (c) Eurasia. The solid line shows a 10-year low-pass filter (order 4). The dashed line shows long-term changes in mean as detected using the sequential algorithm method [Rodionov, 2006; probability level $\sigma = 0.05$; 30-year window with correction for AR(1)]. Refer to Table 2 for linear trend analysis.

index. No significant trend in the percentage of area exceeding 280 MDC units was detected on the North American index.

At the ecoregion scale, July MDC did not exhibit a widely significant positive linear trend over time (Table 3). A positive linear trend was detected for the Northern Canadian Shield taiga ecoregion (Table 3). However, the statistical significance of this trend was obscured by a change in the variance within the July MDC record (Table 3, *F*-test), a bias that may be a result of the paucity of climate stations in the early part of the 20th century (see 'Climate data'). Instead, significant changes toward increasing moisture were detected in five Canadian ecoregions. Four of these were ecoregions located in eastern Canada; the fifth was located on the west coast. No significant changes in summer dryness were detected in Eurasia based on the linear trend method. Median and 5th and 95th percentiles of July MDC per 25-year period also showed relatively stable drought severity conditions throughout the century, with a few exceptions (Fig. 4). Notably, the median of July MDC between the 1901–1925 and 1976–2000 intervals decreased by 22 units in eastern Canadian ecoregions and by 40 units on the west coast. These last changes were significant at the 5% level according to a nonparametric *t*-test (Mann–Whitney test; Zar, 1999). No significant change was observed over Eurasia over these same intervals.

Hypothesis 3: extreme drought years have become more frequent

Occurrence rate of extreme drought years at the ecoregion scale did not exhibit a widely significant upward trend over time according to the statistical test described by Cox & Lewis (1966) [Eqn (8); Table 3]. Only one ecoregion, the Western Great Lakes Forests, recorded a significant trend ($P<0.05$), and it was a negative one. However, visual inspection of occurrence rate estimations with 95% confidence band per 25-year period showed striking changes in the global positioning of highs and lows (Fig. 5). Many ecoregions in which occurrence rates of extreme events (λ) were estimated to be extreme ($\lambda>0.20$) in the early part of the 20th century have recently seen their conditions decrease to low or moderate ($\lambda<0.15$), and vice versa.

Table 2 Linear regression analysis of century-scale trends in percentage of area for MDC drought categories across the (a) Northern Hemisphere, (b) North America, and (c) Eurasia

Area under analysis	R^2	P-value	Slope (% year^{-1})	Durbin–Watson statistics
Northern Hemisphere				
MDC > 160	0.041	> 0.100	–	–
MDC > 200	0.001	> 0.100	–	–
MDC > 240	0.034	0.063	+ 0.036	2.077 (passed)
MDC > 280	0.055	0.018	+ 0.028	2.158 (passed)
North America				
MDC > 160	0.040	0.045	−0.052	1.796 (passed)
MDC > 200	0.008	> 0.100	–	–
MDC > 240	0.003	> 0.100	–	–
MDC > 280	0.005	> 0.100	–	–
Eurasia				
MDC > 160	0.016	> 0.100	–	–
MDC > 200	0.005	> 0.100	–	–
MDC > 240	0.043	0.038	+ 0.057	2.025 (passed)
MDC > 280	0.044	0.035	+ 0.036	2.077 (passed)

Analysis was conducted over the 1901−2002 period in areas experiencing low [monthly drought code (MDC) > 160] to extreme (MDC > 280) July droughts (see Fig. 3). Goodness-of-fit is described by the coefficient of determination R^2 along with statistical significance (P-value). Note that model residuals were tested for normality, independence, and homoscedasticity assumptions.

For instance, three eastern Canadian ecoregions have seen their occurrence rates change from more than one extreme event per 5 years to less than one per 7 years. In the Midwestern Canadian Shield Forests and Western Great Lakes Forests ecoregions (Fig. 6), it decreased to less than one extreme event per 14 years. In Eurasia, reductions were not as important and principally affected the Pannonian Mixed Forests ecoregion. In contrast, the Atlantic Forests and Taiga ecoregions (Fig. 6) have seen their occurrence rates change from less than one extreme event per 7 years to more than one per 5 years. Increases in the occurrence rates of extreme drought years were more important on the Eurasian continent, centered principally on the Okhotsk–Manchurian taiga ($P < 0.10$; Table 3).

Discussion

The Boreal Forests/Taiga and Temperate Broadleaf and Mixed Forests biomes are at the front line of climate change. These extratropical regions have experienced significant warming during the 20th century, reaching nearly 2 °C in northernmost regions (Fig. 7a; also see Trenberth *et al.*, 2007, their fig. 3.9). Our results indicate that over Eurasia, areas experiencing high wildfire risk (MDC > 240) have expanded over the past century by about 5.7% (slope significant at the 5% level). Counterintuitively, summer drought severity did not exhibit a widely significant positive linear trend over time. We attribute the increase in percentage of area affected by drought to more frequent extreme drought years over taiga ecoregions (Fig. 5). While the trend in extreme drought years failed to be significant at the 5% level [according to the Cox & Lewis (1966) statistical test], and although statistical uncertainty around the occurrence rates (λ) was substantial (Figs 5 and 6), the amount of data and the fact that the temporal changes covered large territories (i.e. site replication) allow us to conclude that they are important. Our results give credence to those of Groisman *et al.* (2007) and provide independent evidence for increasing wildfire risk over Eurasian taiga ecoregions.

At the opposite, North America has experienced a significant decrease in the percentage of area affected by moderate drought (MDC > 160), and several boreal/mixed forest ecoregions have recorded a decrease in the occurrence rate of extreme drought years. Contrasting with northern taiga ecoregions, the southern Canadian boreal forest has experienced a significant increase in the amount of summer precipitation during the past century based on CRU data (Fig. 7b). The conclusion obtained from the analysis of these data fits with analyses by Mekis & Hogg (1999) on rehabilitated Canadian precipitation data over the period of 1948 to 1995 (their Table 3). Additionally, southern Canadian boreal regions contrast with other regions in that there was no apparent rise of summer maximum temperatures (Fig. 7a).

The precipitation change in Canadian forested regions would have had a strong incidence on wildfire risk, particularly on the occurrence rate of extreme drought years. In the Midwestern Canadian Shield Forests and Western Great Lakes Forests ecoregions, occurrence rates from 1901 to 2002 decreased by a factor of > 3: one event per ~ 14 years at the turn of the 21st century, compared with one event per 4 years at the beginning of the 20th century (Fig. 6b). In other areas of the southern boreal forest, the changes were less important but nevertheless present. This phenomenon ties in with widely reported changes in fire activity in eastern Canadian boreal forests (refer to 'Introduction'). Extreme wildfire risk at the beginning of the 20th century as inferred from July MDC also ties in with a large area burned in western boreal Quebec that has no present day equivalent in terms of extent. Forest inventories indicate that nearly 22% of total forested areas in this boreal region originate from the 1910s and 1920s (Bergeron *et al.*, 2004a), whereas 47% of the forest stands originate from forest fires that took place before 1850.

Table 3 List of ecoregions along with statistical results on constant variance (*F*-test), linear trend, and constant rate of extreme events tests

Ecoregion	Biome	Longitude (degrees)	Latitude (degrees)	Median of MDC(units)*	*F*-test (*P*-value)†	Linear trend (*P*-value)‡	Constant rate (*P*-value)§
North America							
Interior Alaska-Yukon lowland taiga	Boreal forests/ Taiga	−162.25	65.25	239	–	–	–
Northern Cordillera forests	Boreal forests/ Taiga	−134.25	62.25	198	–	0.004 (−)	–
Muskwa-Slave Lake forests	Boreal forests/ Taiga	−127.25	65.25	247	–	–	–
Northwest Territories taiga	Boreal forests/ Taiga	−126.25	65.25	252	–	–	–
Northern Canadian Shield taiga	Boreal forests/ Taiga	−118.25	65.25	213	0.000	0.015 (+)	–
Mid-Continental Canadian forests	Boreal forests/ Taiga	−113.25	61.25	220	–	–	–
Midwestern Canadian Shield forests	Boreal forests/ Taiga	−109.25	59.25	199	–	–	–
Southern Hudson Bay taiga	Boreal forests/ Taiga	−94.25	58.75	174	–	–	–
Western Great Lakes forests	Temperate broadleaf and mixed forests	−91.56	47.68	192	–	0.003 (−)	0.018 (−)
Central Canadian Shield forests	Boreal forests/ Taiga	−91.25	55.25	166	–	0.005 (−)	0.068 (−)
Eastern forest-boreal transition	Temperate broadleaf and mixed forests	−77.35	47.12	178	–	0.049 (−)	–
Eastern Canadian Shield taiga	Boreal forests/ Taiga	−70.25	59.25	123	0.025	–	–
New England-Acadian forests	Temperate broadleaf and mixed forests	−66.41	46.48	159	–	0.095 (+)	–
Eastern Canadian forests	Boreal forests/ Taiga	−61.25	54.25	127	–	0.030 (−)	0.074 (−)
Eurasia							
North Atlantic moist mixed forests	Temperate broadleaf and mixed forests	−5.87	57.13	130	–	–	–
Atlantic mixed forests	Temperate broadleaf and mixed forests	3.25	50.24	234	–	–	–
Baltic mixed forests	Temperate broadleaf and mixed forests	13.07	54.91	219	–	–	–
Scandinavian and Russian taiga	Boreal forests/ Taiga	14.75	65.25	199	–	–	–
Pannonian mixed forests	Temperate broadleaf and mixed forests	19.67	46.88	217	–	–	–
Central European mixed forests	Temperate broadleaf and mixed forests	23.17	51.45	217	–	–	–
Sarmatic mixed forests		31.08	56.83	219	–	–	–

Continued

Table 3 (*Contd.*)

Ecoregion	Biome	Longitude (degrees)	Latitude (degrees)	Median of MDC(units)*	*F*-test (*P*-value)†	Linear trend (*P*-value)‡	Constant rate (*P*-value)§
	Temperate broadleaf and mixed forests						
West Siberian taiga	Boreal forests/Taiga	71.75	65.75	201	–	–	–
Western Siberian hemiboreal forests	Temperate broadleaf and mixed forests	76.88	56.00	252	–	–	–
East Siberian taiga	Boreal forests/Taiga	87.75	65.75	213	0.057	–	–
Trans-Baikal conifer forests	Boreal forests/Taiga	110.75	55.25	206	–	–	–
Northeast Siberian taiga	Boreal forests/Taiga	125.75	65.75	201	0.065	–	–
Manchurian mixed forests	Temperate broadleaf and mixed forests	128.02	49.18	181	–	–	0.069 (–)
Okhotsk–Manchurian taiga	Boreal forests/Taiga	139.75	58.25	147	–	–	0.098 (+)

*Median of July MDC over the 1901–2002 period. Thresholds for drought severity classes are (i) low ($\text{MDC} < 160$), (ii) moderate ($\text{MDC} < 200$), (iii) high ($\text{MDC} < 240$), and (iv) extreme ($\text{MDC} \geq 240$).

†*P*-value of the *F*-test conducted between the 1901–1920 and 1921–2002 periods. The hypothesis that the standard deviations of the two populations are equal is rejected when $P < 0.05$ (may indicate a potential bias originating from data interpolation).

‡*P*-value of the linear trend of July MDC over the 1901–2002 period (tested using the Spearman correlation coefficient). The hypothesis that the slope is not different from zero is rejected when $P < 0.05$ (also tested for red noise bias as described by von Storch & Zwiers, 1999). The direction of the trend is indicated by + (positive) and – (negative) signs.

§*P*-value of the test for constant occurrence rate [see Eqn (8)] described by Cox & Lewis (1966). The hypothesis that the occurrence rate is constant is rejected when $P < 0.05$.

MDC, monthly drought code.

The increase in summer precipitation and decrease in the occurrence rate of extreme drought years in western boreal Quebec also concur with a reported long-term increase in growth of *Thuja occidentalis* L. on rocky outcrops, a species known for being moisture limited in such an environment (Archambault & Bergeron, 1992; Buckley *et al*., 2004; Girardin *et al*., 2004a). Our results provide solid arguments for a climate-induced change in fire activity in western and eastern Canada. Although they cannot be totally ruled out, the influence of native people and of European settlers on fire activity before 1920 and the effectiveness of fire suppression afterward cannot explain alone the observed decrease in fire activity over these territories.

Wildfire occurrence and spread follow day-to-day variations in weather and are often the results of complex interactions between precipitation, temperature, humidity, solar radiation, ignition agents and wind (Van Wagner, 1987; Flannigan & Harrington, 1988). Additionally, these features depend largely on the horizontal and vertical state of the atmosphere. Therefore, summer moisture in deep layers of the forest floor, as modeled by July MDC, is unlikely to explain all year-to-year variations in area burned. For all five regions studied, the amount of shared variance between AAB and MDC varied between 25% and 61%. Nevertheless, these numbers compare well with other values reported in the literature obtained from more complex fire weather indices that integrate weather daily observations. Groisman *et al*. (2007) attributed 53% of the seasonal variance in the number of fires in Ontario to the number of summer days with modified Nesterov and Zhdanko drought indices exceeding the upper 10th percentiles, which is not more significant than our r^2 of 0.50 (refer to 'Hypothesis 1: area burned is significantly correlated to summer MDC'). Furthermore, the performance of the July MDC in predicting seasonal fire activity in the state of Alaska is very similar to that of the Keetch–Byram Drought Index (KBDI) also used by Groisman *et al*. (2007): both indices can capture about 40% of the variance in Alaska's AAB (Fig. 8). The two indices also show high similarities (Fig. 8c), even

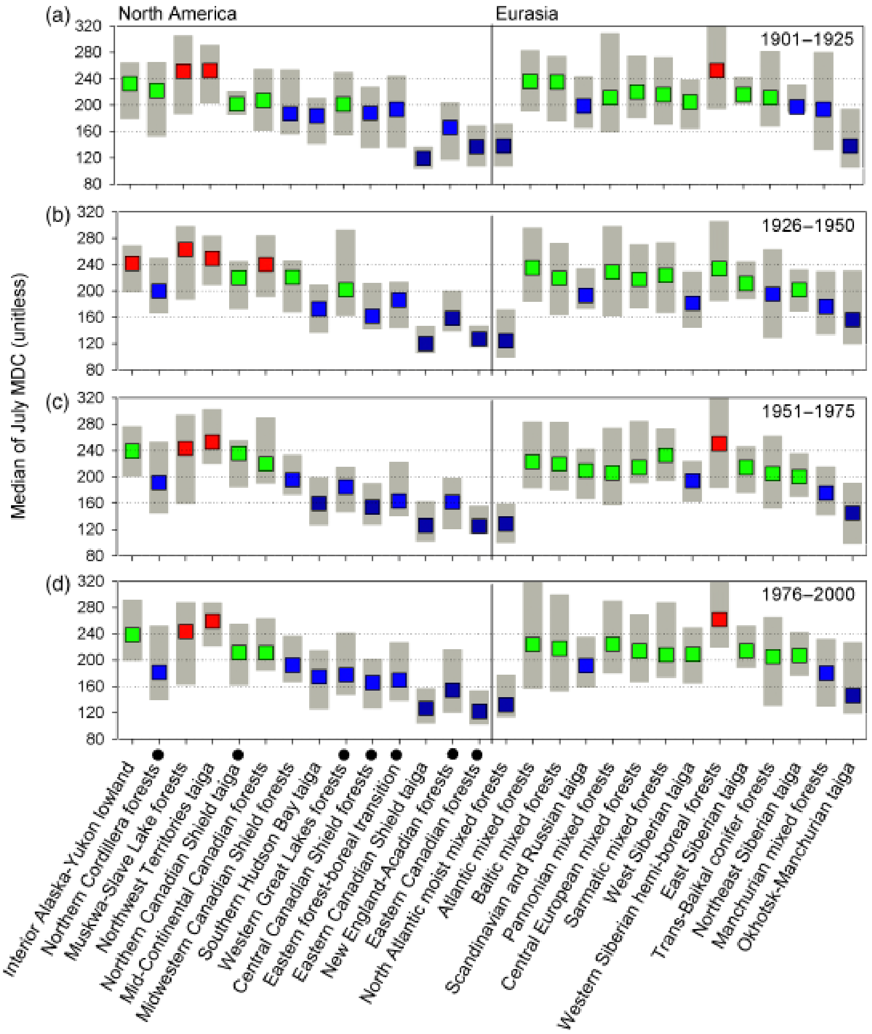

Fig. 4 Median, 5th and 95th percentiles (grey bars) of July monthly drought code (MDC) per 25-year period. Ecoregions are aligned from west to east. Colors refer to wildfire condition classes: low (dark blue: MDC <160), moderate (blue: MDC <200), high (green: MDC <240), and extreme (red: MDC ≥ 240). Ecoregions marked with '●' passed the $P<0.10$ threshold in the detection of a linear trend over the 1901–2002 period ($P<0.05$; see Table 3 for details).

though the KBDI shows skewness in the upper tail of its frequency distribution. For the Komi Republic, Drobyshev & Niklasson (2004) attributed 59% of the AAB variance from 1950 to 1990 to variations in the Seljaninov hydrothermal coefficient (SHC; Shvidenko *et al*., 1998). The SHC is a simple ratio of the sums of daily temperature and daily precipitation over the period of June to August. Our regional average of July MDC (Fig. 2f) did not perform as well as did the daily SHC in predicting wildfire risk. However, we have found similar correlation when analyzing the Komi Republic fire data against MDC grid points from locations close to weather stations used by Drobyshev & Niklasson (2004) ($r^2 = 0.50$ at locations ~52.75°W; 61.75°N; $r^2 = 0.58$ after detrending).

Flannigan *et al*. (2005) attributed 36–60% of the monthly area burned across various ecozones of Canada over the 1959–1997 period to multivariate combinations of monthly temperature, relative humidity, and Canadian FWI system components. In their study, the DC was rarely selected by their regression models as a significant predictor of monthly area burned. This is likely because of the monthly time-step used in their analyses, which might not work very well with the long drying constant rate of the DC (and therefore MDC). In an analysis of the relationship between AAB and monthly fire weather indices and temperature over a 2.5° (latitude × longitude) resolution grid ($n = 127$) across Alaska and Canada, Balshi *et al*. (in press) found the July DC to be second most frequently accurate fire

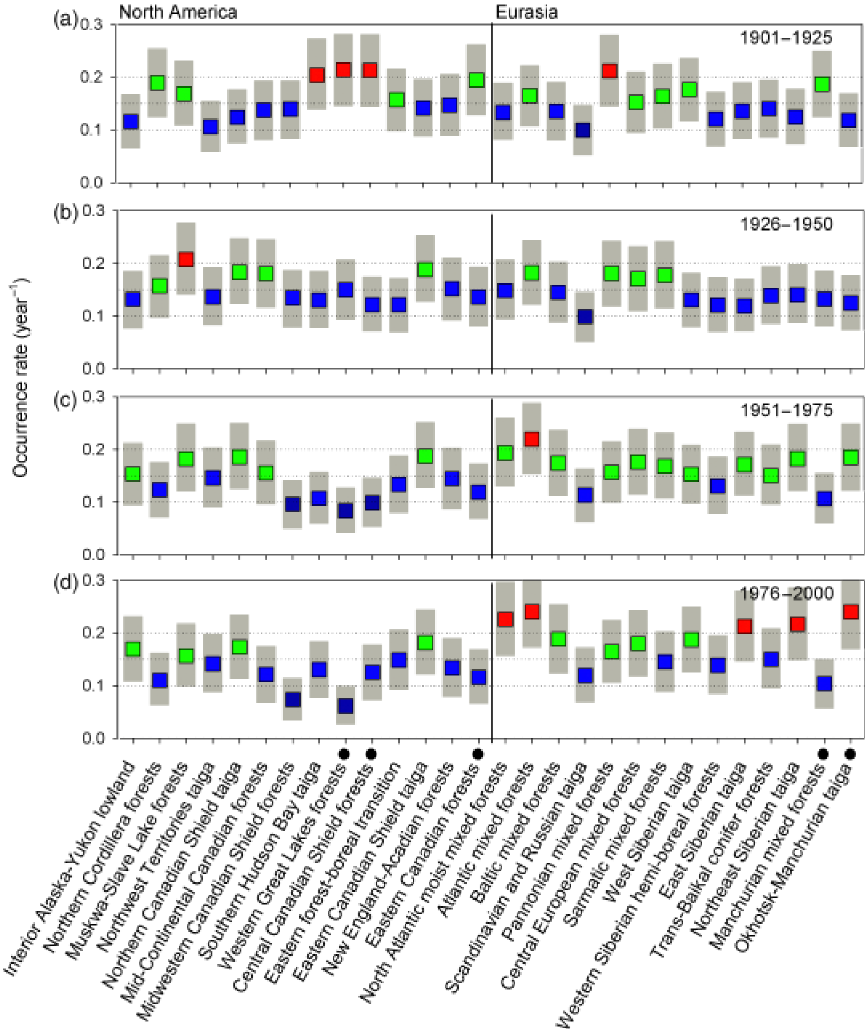

Fig. 5 Extreme wildfire risk estimated as rate of occurrence (year^{-1}) of extreme drought years via a kernel approach (bandwidth parameter $h = 25$, endpoint of each window is shown; based on Mudelsee, 2002; Mudelsee *et al.*, 2004). Bootstrap simulations ($n_{\text{sim}} = 10\,000$) yield 90% confidence bands (grey shading) for risk estimates. Colors refer to wildfire condition classes: low (dark blue: less than one extreme event per 10 years), moderate (blue: one extreme event per 7–10 years), high (green: one extreme event per 5–7 years), and extreme (red: more than one extreme event per 5 years). Ecoregions marked with ' ● ' passed the $P < 0.10$ threshold in the detection of a nonconstant rate (see text for details and Table 3 for statistical results).

predictor ($n = 23$; their Table 1), after July air temperature ($n = 33$). They also attributed 87% of the area burned variance in Canada west of 90°W to multivariate combinations of fire–weather parameters. This predictive performance was superior to that of the July MDC (Fig. 2b). That being said, Girardin & Wotton (in press) were able to predict 60% of the countrywide AAB variance (in hectares) from July MDC by down-weighting regions of low fire activity from their aggregated MDC record. Additionally, Balshi *et al.* (in press) found low levels of fire predictability for eastern Canada, with all indices taken into account. Our results showed otherwise, with nearly 60% of the variance in area burned explained by July MDC for provincial units such as Ontario and Quebec over periods during which fire statistics were thought to be minimally biased. We thus argue that there is a high level of predictability of fire activity in eastern Canada and elsewhere based on the MDC (see also Girardin *et al.*, 2004a, 2006).

The current study has a number of limitations. Although the MDC performed fairly well at predicting wildfire risk, in many regions there is either a distinctly thin or absent deep duff layer. Instead, we often find vegetation growing mostly on rock or sand. Under such conditions, the value of July MDC is arguably questionable, and indices with shorter drying lags are likely to be better surrogate for duff moisture content (Van Wagner, 1987) and for evaluating climate change

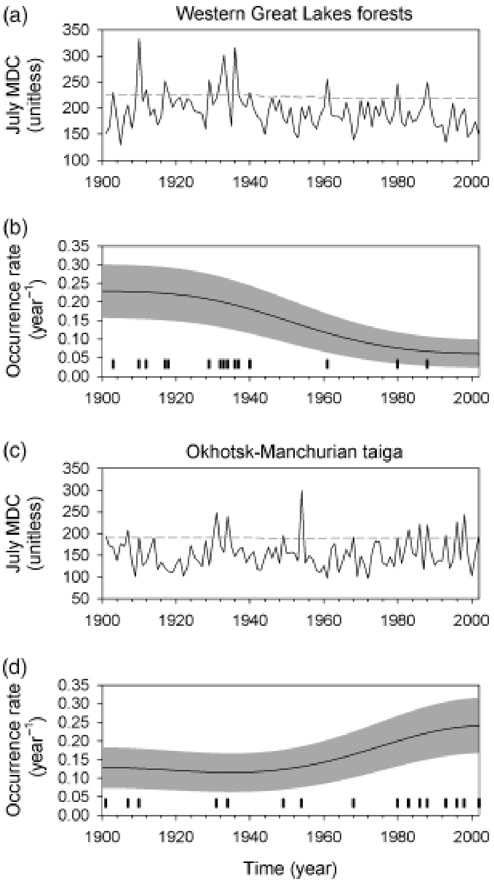

Fig. 6 Examples of occurrence rate estimation of extreme drought years. (a) and (c) July MDC records of Western Great Lakes forests and Okhotsk–Manchurian taiga ecoregions. The thresholds for detection of extreme fire years ($k = 40$) are shown with dashed lines. (b) and (d) Extreme wildfire risk estimated as rate of occurrence (year^{-1}) of extreme drought years (*vertical marks*) via a kernel approach, with 90% confidence bands (grey shading) for risk estimates. MDC, monthly drought code.

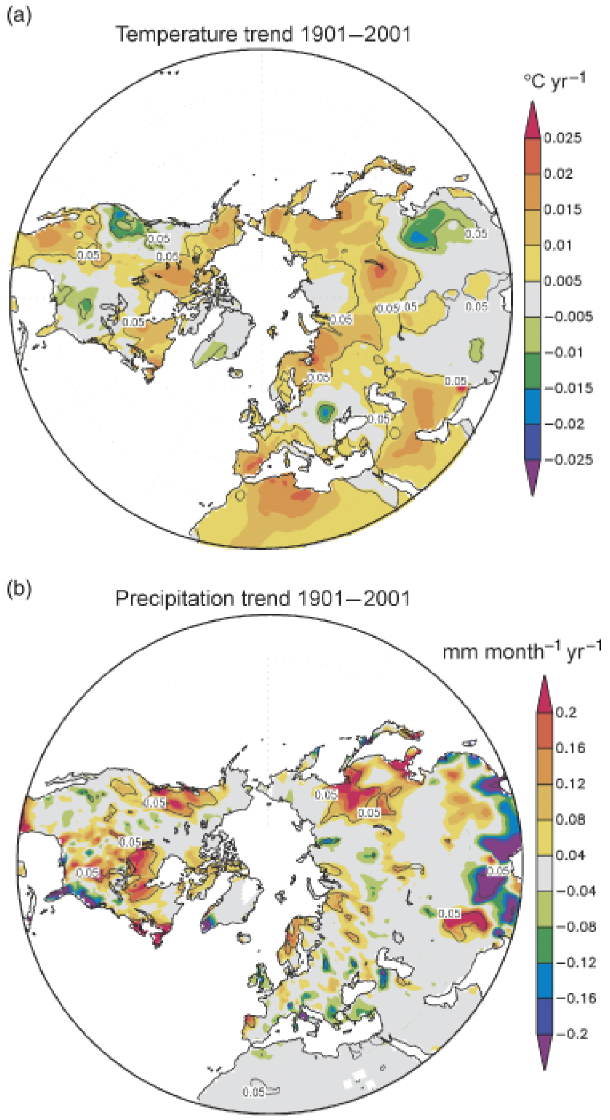

Fig. 7 Linear trend in Northern Hemisphere May to July maximum temperatures (°C yr^{-1}) and total precipitation (millimeters per month per year) for 1901 to 2001 (data from the Climate Research Unit, 1.0° × 1.0° grid). Contours delineate the 5% significance level. Maps were constructed using the Climate Explorer (http://climexp.knmi.nl/).

impacts on wildfire risk. Furthermore, our interpretations 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 have modulated long-term trends in fire activity during the 20th century. For instance, the current analyses are restricted to the seasonal period of maximum fire activity, May to July. The fire seasons in the northwestern Canadian boreal forest have been shown to shift to later season burns in recent years (Kasischke & Turetsky, 2006). 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 our estimates of wildfire risk. Deeper seasonal thawing as a consequence of global warming could, for instance, positively feed on fire activity in Taiga ecoregions. Other factors that may be worthy of 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 behavior (Li *et al*., 2000), changes in ignition agents (lightning frequency and human-caused ignition; Price & Rind, 1994; Wotton *et al*., 2003), changes in land use (e.g. fragmentation of landscapes and fire suppression; Niklasson &

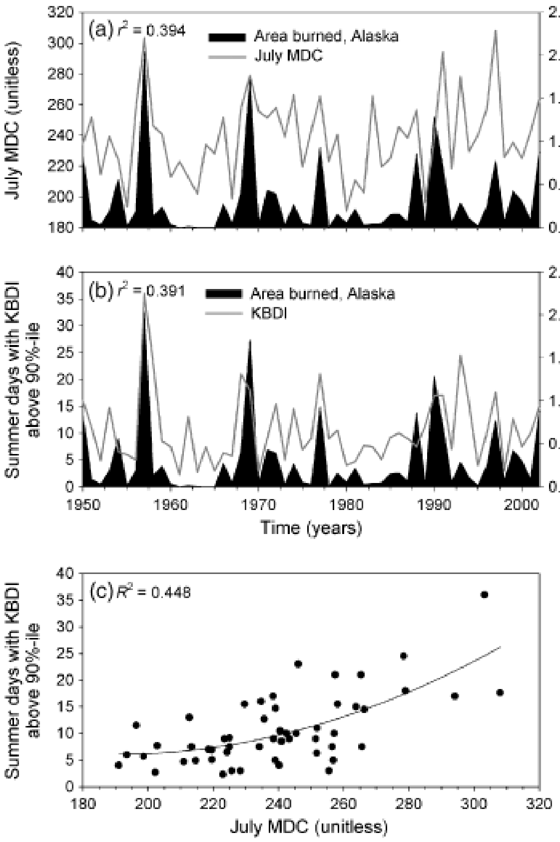

Fig. 8 (a) July MDC and (b) the frequency of high Keetch–Byram Drought Index (KBDI) values in Alaska vs. state-wide area burned (in millions of hectares). The square of the Spearman rank correlation (r^2) expresses the goodness-of-fit between data. (c) Relationship between MDC and KBDI. R^2 represents the amount of shared variance between both data captured by a two-order least-squares regression. KBDI data were obtained from Groisman *et al.* (2007; their fig. 10). MDC, monthly drought code.

Granström, 2000; Lefort *et al.*, 2004; Cumming, 2005), interactions with other natural disturbance agents such as insect outbreaks and diseases, etc.

Two statistical aspects of climate variability were evaluated in this study: location (i.e. median of July MDC or the typical situation) vs. departures (15th percentile or extreme events). As demonstrated by our analyses of wildfire risk over Eurasian Taiga ecoregions during 1901−2002, the two aspects may act independently from each other. While the typical situation has remained relatively stable over time in the Okhotsk–Manchurian taiga, the departures have increased, giving rise to more extreme conditions in recent years (compare Figs 4 and 5). In forest ecology, the two aspects (location and deviation) are fundamentally important. For instance, we can hypothesize that increases in extreme drought years that are not accompanied by increases in the median of drought severity may cause disturbance regimes to be more episodic (or 'pulse' dependant; Bouchard *et al.*, 2008). Such a transition may be accompanied by notable effects on forest age structures, forest compositions and biodiversity, and spatial arrangements of forest mosaics. Such a disconnection between location and departures has already been found by Carcaillet *et al.* (2001) in their reconstruction of Holocene fire history from charcoal particles preserved in lake sediments in the Central Canadian Shield forest: more fires were recorded in the last 2000 years than at earlier times in spite of increasing lake levels (Carcaillet *et al.*, 2001). While on average climate has become wetter at decadal to centennial time-scales, an increasing frequency of drought years has favored fire spread (Carcaillet *et al.*, 2001). We wish to emphasize that risk analyses strictly focused on the detection of linear trends in fire weather components may fail to detect important changes in this natural hazard that is wildfire. Such 'false negative' results, which have been encountered in previous studies (e.g. Amiro *et al.*, 2004; Girardin *et al.*, 2004b), can lead to misinterpretation of processes (climate vs. human and vegetation factors) leading to changing fire activity and may have notable effects on projections of climate change impacts on boreal and taiga forests.

Conclusion

We addressed changes in wildfire risk over the 1901−2002 period with an analysis of broad-scale patterns of July MDC variability on forested ecoregions of North America and Eurasia. Our analyses did not reveal widespread patterns of linear increases in dryness through time as a response to rising Northern Hemisphere temperatures. Instead, we found heterogeneous patterns of drought severity changes that were inherent to the nonuniformly distributed impacts of climate change on Northern Hemispheres lands. Notably, significant trends toward increasing summer moisture in southern boreal Canada were detected. The diminishing wildfire risk in these regions is coherent with widely reported decreases in the area burned since about 1850, as reconstructed by dendrochronological dating of forest stands (see Introduction). Conversely, we found some evidence for increasing percentage of area affected by extreme droughts and occurrence rates of extreme drought years in northern taiga ecosystems (mostly over Eurasia). Although not all these changes were statistically significant, the fact that the temporal changes covered large territories allows us to conclude that they are sufficiently important to be worthy of further attention.

Acknowledgements

This collaboration was made possible thanks to funding from the 61ème Commission permanente de cooperation franco-québécoise. Thanks are extended to Héloïse Le Goff, Isabelle Lamarre and Pamela Cheers for their comments and for reviewing the manuscript. We thank the MRNFQ for providing the Quebec fire statistics.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Locations across North America and Russia where regional wildfire statistics were made available for this study.