PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B

Phil. Trans. R. Soc. B (2008) **363**, 2317–2329
doi:10.1098/rstb.2007.2202

Climate and wildfires in the North American boreal forest

Marc Macias Fauria[1,2,3,4,*,†] **and E. A. Johnson**[1,2]

[1]*Department of Biological Sciences, and* [2]*Biogeoscience Institute, University of Calgary, Calgary, Alberta, Canada T2N 1N4*
[3]*Department of Geology, Univesity of Helsinki, 00014 Helsinki, Finland*
[4]*Department of Ecology, University of Barcelona, 08028 Barcelona, Spain*

The area burned in the North American boreal forest is controlled by the frequency of mid-tropospheric blocking highs that cause rapid fuel drying. Climate controls the area burned through changing the dynamics of large-scale teleconnection patterns (Pacific Decadal Oscillation/El Niño Southern Oscillation and Arctic Oscillation, PDO/ENSO and AO) that control the frequency of blocking highs over the continent at different time scales. Changes in these teleconnections may be caused by the current global warming. Thus, an increase in temperature alone need not be associated with an increase in area burned in the North American boreal forest. Since the end of the Little Ice Age, the climate has been unusually moist and variable: large fire years have occurred in unusual years, fire frequency has decreased and fire–climate relationships have occurred at interannual to decadal time scales. Prolonged and severe droughts were common in the past and were partly associated with changes in the PDO/ENSO system. Under these conditions, large fire years become common, fire frequency increases and fire–climate relationships occur at decadal to centennial time scales. A suggested return to the drier climate regimes of the past would imply major changes in the temporal dynamics of fire–climate relationships and in area burned, a reduction in the mean age of the forest, and changes in species composition of the North American boreal forest.

Keywords: Alaska; area burned by wildfire; Canada; climate change; Pacific Decadal Oscillation; Arctic Oscillation

1. INTRODUCTION

Lightning-caused wildfires are the main disturbance in the North American boreal forest. The boreal forest is a mosaic of stands of different ages since they last burned. Large fires account for over 85% of the total area burned but less than 5% of the fires. The landscape of the boreal forest is thus determined *not* by the numerous small fires but by the infrequent large fires (Johnson *et al.* 1998; Stocks *et al.* 2003). The frequency of large fire years, and thus area burned, in Canada has increased in the last four decades of the twentieth century (figure 1). Such increases have been attributed in part to global warming (Gillett *et al.* 2004; Skinner *et al.* 2006).

The northern latitudes are expected to suffer the largest temperature increases under a global change scenario (IPCC 2001). Based on this, general circulation models have been used to predict increases in area burned of up to 118% from the present in doubled and tripled CO_2 scenarios by the end of the twenty-first century (Gillett *et al.* 2004; Flannigan *et al.* 2005). Overall, the area burned in Canada is predicted to increase due to an increase in temperature, despite regional differences—for example predicted decreases in area burned for the eastern North American boreal forests (Flannigan *et al.* 1998; Carcaillet *et al.* 2001).

Besides the increase in area burned, the increase in temperatures associated with climate warming by increased CO_2 has been predicted to lengthen the fire season (e.g. Street 1989; Wotton & Flannigan 1993; Stocks *et al.* 1998; Flannigan & Wotton 2001; Flannigan *et al.* 2005) and also to increase its intensity due to the increased drying capacity of the air (Street 1989; Johnson 1993). The fire season (defined in terms of area burned and not number of fires) in the boreal forest of North America is relatively short and spans from May to August, starting earlier in the southern parts of the boreal forest and later further north. Typically, the area burned peaks between the second half of June and the first half of July, followed by a sharp reduction in August. Latitudinal changes have been related to the spring northward advance (and the progressive penetration of warm Pacific air into the continent) and the autumn southward advance of the polar front (Johnson 1992). In the western mixedwood boreal forest, changes in the length of the fire season during the last two centuries have been reported (Johnson *et al.* 1999), with longer fire seasons before the late nineteenth century, synchronous with a period of higher fire activity.

An increase in area burned and in the frequency of large fire occurrence would change the landscape age distribution and reduce the mean age of the boreal

---

[*] Author for correspondence (marc.macias@helsinki.fi).
[†] Present address: Department of Ecology, University of Barcelona, 08028 Barcelona, Spain

One contribution of 12 to a Theme Issue 'The boreal forest and global change'.

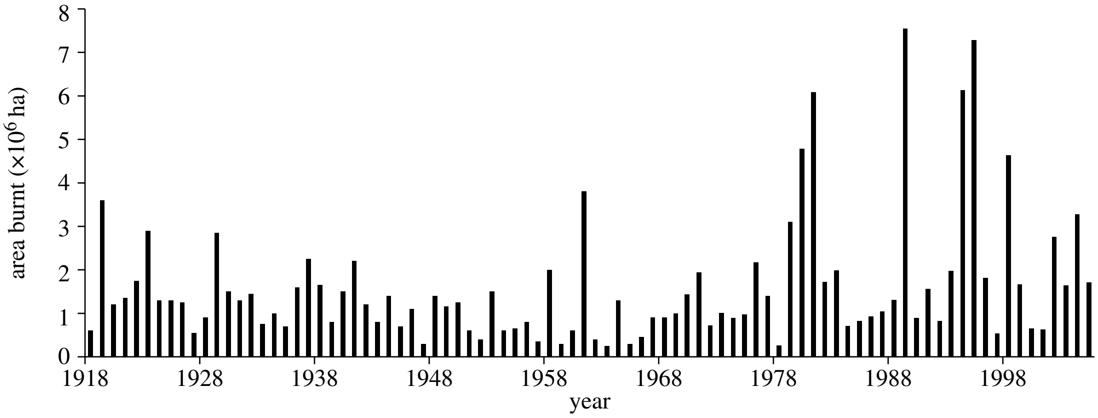

Figure 1. Annual forested area burned in Canada for the period 1918–2005.

forest (e.g. Johnson & Fryer 1989; Johnson 1992). This would probably have implications for species distribution, for example, favouring species with earlier reproductive ages. Desponts & Payette (1993) found that a reduced interval between fires favours jack pine (*Pinus banksiana* Lamb.) over black spruce (*Picea mariana* Mill.).

A change in the area burned might also change the shapes of polygons within the landscape age mosaics, with shorter average fire intervals resulting in an age mosaic of younger, larger oblong-shaped polygons with irregular edges (Weir *et al.* 2000). Finally, an increase in the area burned would have consequences for the global carbon budget. Traditionally, higher fire activity in the boreal forest has been predicted to enhance carbon emissions and diminish (if not completely reverse) the role of the boreal forest as a carbon sink (Kasischke *et al.* 1995; Kurz & Apps 1999). Later studies have suggested different outcomes, depending on the frequency of fires, when taking into account changes in the albedo related to fires (Randerson *et al.* 2006).

However, to understand if global warming will increase the area burned in the boreal forest, it is essential that we understand the mechanisms that link weather and climate to area burned. Increases in temperature alone do not explain increases in area burned. In fact, most studies on fire frequency in the boreal forest of North America show that, despite significant increases in temperature since the end of the Little Ice Age, the frequency of fires decreased in the last 150 years (e.g. Bergeron & Brisson 1990; Flannigan *et al.* 1998; Lesieur *et al.* 2002). That is, an increase in temperature in the last 150 years did not increase the area burned, until the last decades of the twentieth century. This increase in recent decades is probably not due to fire suppression since large parts of the boreal forest are not subject to fire protection.

The objective of this paper is to describe what is known at present about the connection between large-area-burned years and the weather and climate that appear to cause these events. We do so in the following order:

(i) The first part of the paper explains in detail the kind of wildfires that occur in the North American boreal forest and how these wildfires are related to climate.
(ii) Next, we address how climate has controlled large fire occurrence during the last decades of the twentieth century.
(iii) Then, the focus turns to what is known about the long-term past fire frequency (before fire reports), using cumulative time-since-fire distributions obtained from time-since-last-fire maps and palaeoecological studies based on lake sediments, macrofossils and ice cores.
(iv) Finally, the different time scales of the climate–wildfire system are considered to address what effect global warming might have on the North American boreal forest.

2. THE RELATIONSHIP BETWEEN FIRE AND CLIMATE

In the boreal forest, crown fires (as opposed to surface fires) are the dominant fire behaviour (Johnson 1992; Johnson *et al.* 2001) and, generally, fuel moisture (weather) and not fuel accumulation are the primary determinant of fire behaviour (Bessie & Johnson 1995; Johnson *et al.* 2001; Keeley & Fotheringham 2001). This is because wildfires are propagated primarily by fine fuels which, in closed-canopy boreal forests, are relatively constant after canopy closure at 15 or 20 years.

The large area burned in the boreal forest of North America is related to the presence of a persistent (more than 10 days) mid-tropospheric (500 hPa) ridge (Schroeder *et al.* 1964; Newark 1975; Alexander *et al.* 1983; Fryer & Johnson 1988; Johnson & Wowchuk 1993); for example, large fire years in the Yukon Territory are characterized by persistent high pressures over this region (figure 2). Under such conditions, zonal air flow is blocked, enhancing meridional inflow of warm air and dominant air subsidence, both of which generate warmer and drier weather. These conditions result in rapid drying of fuels over large areas and high fire hazard (e.g. Johnson & Wowchuk 1993). Several authors have found empirically that the most fire-prone situations occur when the upper air ridge is located directly above or immediately upstream of the area burned (Street & Birch 1986; Skinner *et al.* 1999; Macias Fauria & Johnson 2006). Thus, the frequency of mid-tropospheric blocking highs relates to a large area burned in the boreal forest.

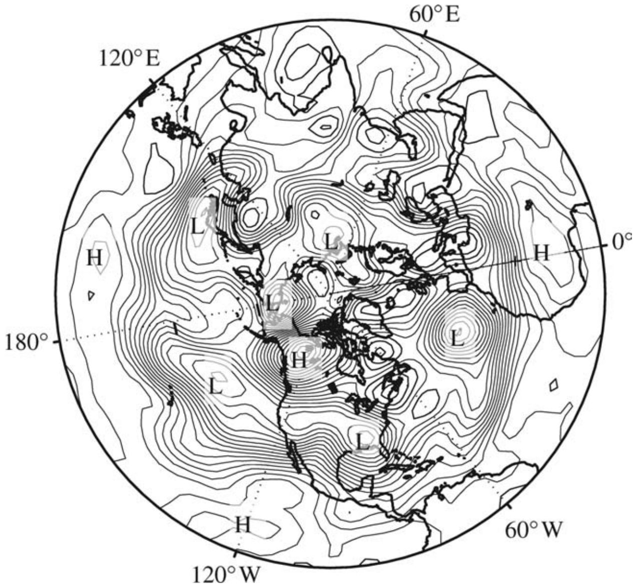

Figure 2. Northern Hemisphere 500 hPa height anomaly chart for large fire years in Yukon Territory. *H*, high geopotential height anomalies; *L*, low geopotential height anomalies. Note the prominent mid-tropospheric blocking highs over the area of Yukon Territory (northwest Canada) .

Large fires usually occur during the breakdown of these persistent mid-tropospheric ridges and are associated with the occurrence of troughs (short waves) that generate strong surface winds, enhance lightning and do not produce enough rain to moisten the fuel (Flannigan & Harrington 1986; Street & Birch 1986).

(a) *Large-scale fire–climate relationships*

Johnson & Wowchuk (1993) described how large fire years in the southern Canadian Rocky Mountains were related to the positive phase of the Pacific North American (PNA) teleconnection (Dickson & Namias 1976; Namias 1978; Wallace & Gutzler 1981). The positive mode of the PNA consists of high 500 hPa heights centred over western Canada and low heights over the North Pacific and southeast USA (figure 3). This finding pointed out, for the first time, the importance of large-scale Northern Hemisphere climatic mechanisms in fire occurrence.

The main features of the normal climatological summer (fire season) flow in northern North America for the last half of the twentieth century (figure 4) are (i) a weak southward-extending trough located adjacent to the west coast of North America—the west coast trough (WCT), (ii) a parallel strong northward-extending ridge over western and northwestern North America, ranging from the west coast to approximately 110° W and extending from the mid-latitudes to Alaska—the western Canadian ridge (WCR), (iii) a strong southward-extending trough over northeastern North America—the Canadian Polar trough (CPT; Skinner *et al.* 1999) and, finally (iv) upper air height variability over the Arctic Ocean (figure 5, see below).

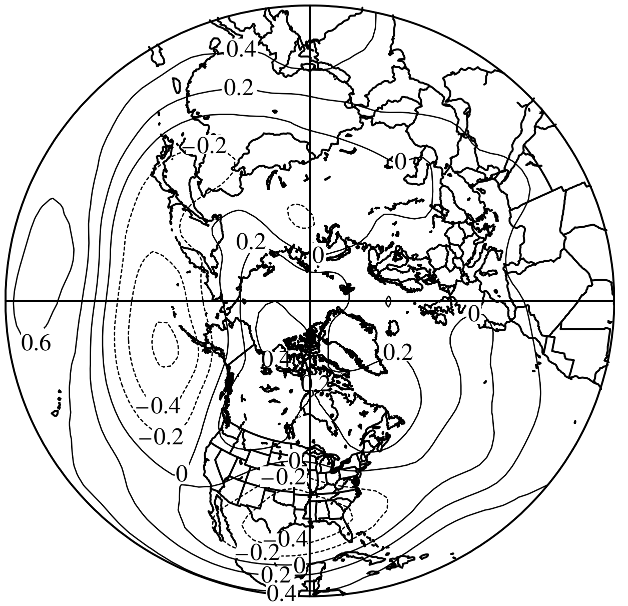

Figure 3. Chart showing point correlations between Northern Hemisphere 500 hPa height and PNA index, based on spring–summer (March–August) anomalies. Contour interval is 0.2. Note the most prominent patterns of positive PNA—highs over western North America and lows in the Gulf of Alaska and southeastern USA. Data and software for the figure obtained from the NCEP/NCAR Reanalysis Project (Kalnay *et al.* 1996).

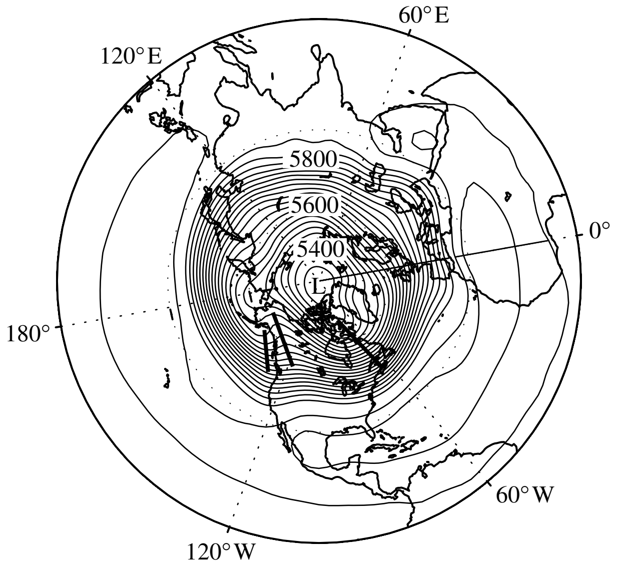

Figure 4. Mean mid-tropospheric (500 hPa) Northern Hemispheric flow during the fire season (defined as May–August) for the period 1959–1999. The main circulation features are shown as vertical lines. From west to east these are: west coast trough (WCT), western Canadian ridge (WCR) and Canadian polar trough (CPT) .

Large fires are usually linked to positive 500 hPa anomalies that correspond to amplifications (eastward, northward and northwestward) of an anomalously strong WCR and to an eastward shifted and sometimes weakened CPT (Skinner *et al.* 1999; Macias Fauria & Johnson 2006). The WCR can sometimes be displaced eastward by an eastward-displaced WCT (e.g. Macias Fauria & Johnson 2006).

Such patterns are related to two main large-scale climatic patterns that have their origin in Northern Hemispheric (and even global) atmosphere and atmosphere–ocean interactions: the Arctic Oscillation (AO) and the Pacific Decadal Oscillation (PDO)—El

Niño Southern Oscillation (ENSO; Macias Fauria & Johnson 2006). The AO or northern annular mode (NAM; Trenberth & Paolino 1981; Wallace & Gutzler 1981; Thompson & Wallace 1998, 2000) is defined as the dominant pattern of sea-level pressure (SLP) variations north of 20° N and is characterized in its positive (negative) phase by negative (positive) SLP anomalies in the Arctic and positive (negative) anomalies at mid-latitudes (figure 5). The AO pattern is found to extend from the surface to the stratosphere, hence reflecting the strength of the polar vortex (Thompson & Wallace 1998; Serreze *et al.* 2000). The AO is closely related to the North Atlantic Oscillation (NAO; van Loon & Rogers 1978).

The PDO (figure 6) is the leading mode of monthly sea surface temperature (SST) in the North Pacific Ocean, north of 20° N (Hare 1996; Mantua *et al.* 1997; Zhang *et al.* 1997). PDO events persisted for 20–30 years during the twentieth century. Warm (cool) PDO phases were characterized by a strengthened (weakened) Aleutian low, enhancing (reducing) the advection of warmer air onto the west coast of North America, which caused positive (negative) temperature anomalies over northern North America with the largest anomalies located over central Canada (Minobe 1997; Mantua & Hare 2002). Warm PDO phases tend to produce persistent high-pressure anomalies over northern North America, especially over western Canada and Alaska (Zhang *et al.* 1997). The PDO is related to SST, precipitation and convection variability in the Indian Ocean and tropical Pacific Ocean, and its spatial climatic patterns are similar to the ENSO pattern (Mantua *et al.* 1997; Zhang *et al.* 1997).

(b) *Large-scale climate and large lightning fires in the boreal forest of North America, 1959–1999*

Macias Fauria & Johnson (2006) showed how the large area burned in Canada and Alaska has been linked during the last four decades to the action and interaction of the PDO/ENSO and AO systems. As noted above, the climatic fingerprints of ENSO and PDO are very similar and can only be separated by the frequency bands at which they operate. The PDO is related to fire climate at low frequencies (decadal variability), whereas ENSO and especially AO are related to fire climate at much shorter time scales (months to a few years; table 1). The ENSO typically operates at scales of 2–6 years (Minobe 2000) and the PDO operates at longer frequencies. The interactions between interannual ENSO events (El Niño and La Niña) and interdecadal PDO suggested that typical El Niño patterns over North America are strong and consistent only during the positive (warm) phase of the PDO, whereas strong La Niña patterns over the continent are associated with the negative (cool) PDO phase (Gershunov & Barnett 1998).

The large area burned in western Canada, and much of the area burned in Alaska (e.g. Hess *et al.* 2001; Macias Fauria & Johnson 2006), occurs under positive PDO phases, with strong advection of warm Pacific air into the continent (figure 7). Moist, warm Pacific air west of the Canadian Rocky Mountains prevents large-fire weather conditions (some large fire years were also linked to positive PDO in British Columbia (e.g. 1985), but such events were rare during the period 1959–1999). Thus, area burned patterns in British Columbia are in anti-phase with those patterns east of the Rocky Mountains. Many large fire situations in eastern Canada were also directly related to a PDO situation with a WCR having an extreme eastward extension (figure 7).

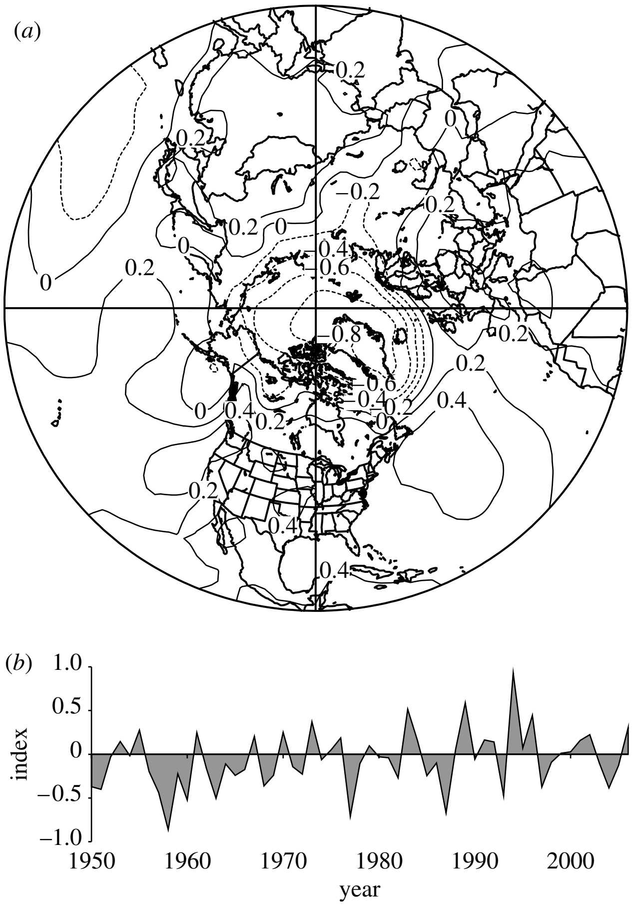

Figure 5. The Arctic Oscillation (AO). (*a*) Chart showing point correlations between Northern Hemisphere sea-level pressure (SLP) and Arctic Oscillation, based on the fire season (May–August) anomalies. Contour interval is 0.2. Note the most prominent patterns of positive AO—lows over the Arctic Ocean and a belt of highs at mid-latitudes, especially prominent in the north Atlantic. Data and software for the figure obtained from the NCEP/NCAR Reanalysis Project (Kalnay *et al.* 1996). (*b*) Summer (June–August) AO index, obtained from the National and Ocean and Atmospheric Administration (NOAA; http://www.cpc.noaa.gov/).

On the other hand, the positive AO has been shown to be related to frequent summer ridging over the eastern part of the North American boreal forest and a large area burned (figure 7). Some fires in Alaska and the northern parts of the Northwest Territories in Canada have been linked to negative AO situations, in which a southward extension of a high-pressure anomaly centred in the Arctic Ocean has affected these areas.

It is noteworthy that during 1959–1999, AO-related large fires in the eastern boreal forest (mainly Québec) only occurred under a positive PDO phase, suggesting an AO–PDO/ENSO interaction. However, this conclusion is based on a limited study period comprising only one cool and one warm regime of the PDO.

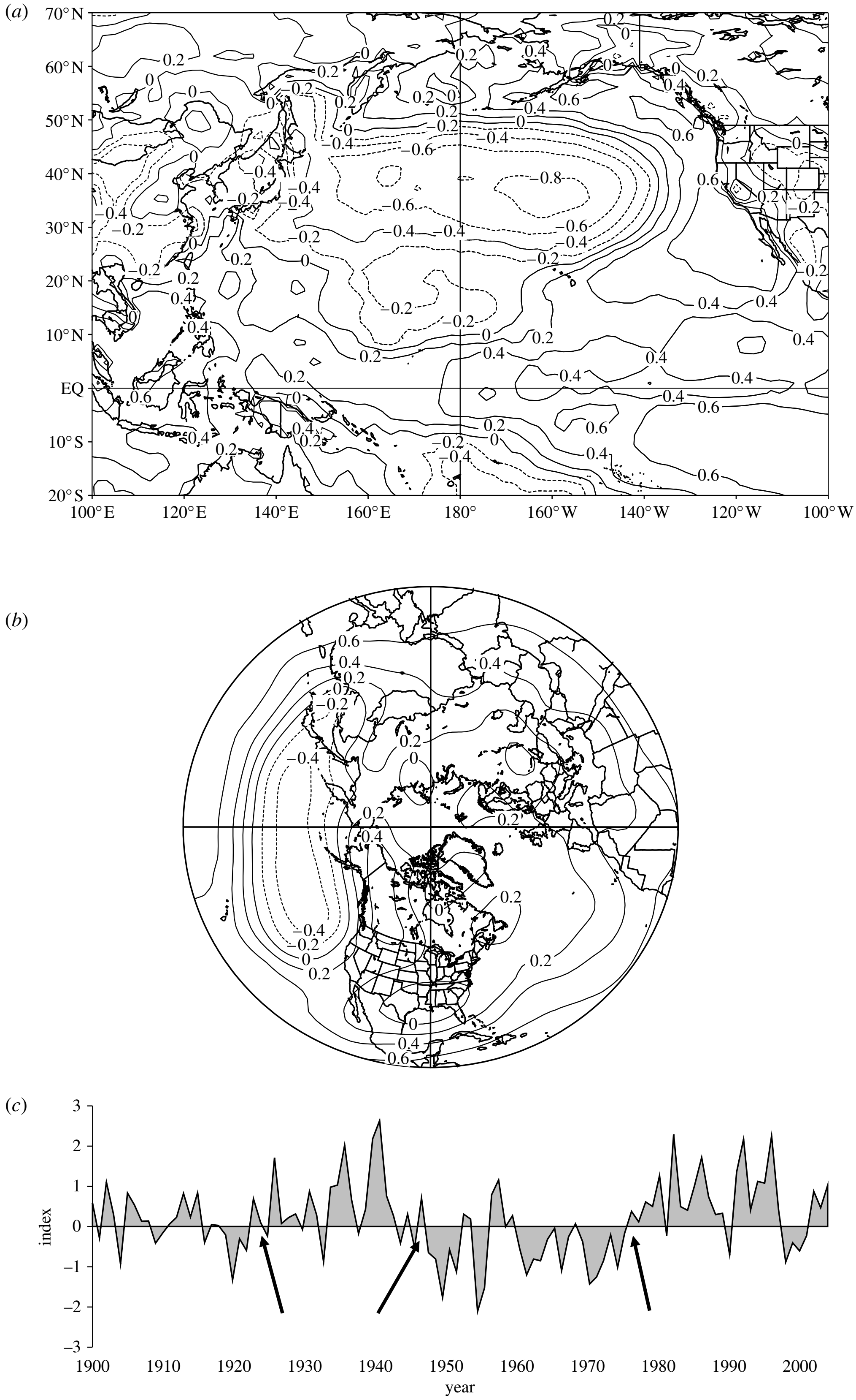

Figure 6. The Pacific Decadal Oscillation (PDO). (*a*) Chart showing point correlations between Northern Pacific Ocean Sea Surface Temperatures (SST) and the PDO Index, based on spring–summer (March–August) anomalies. Contour interval is 0.2. Note the most prominent patterns of positive PDO—high temperatures in front of the northwestern coast of North America and in the Gulf of Alaska, and low temperatures in the central North Pacific Ocean. Data and software for the figure obtained from the NCEP/NCAR Reanalysis Project (Kalnay *et al.* 1996). (*b*) Chart showing point correlations between Northern Hemisphere 500 hPa height and the PDO index, based on spring–summer (March–August) anomalies. Contour interval is 0.2. Note the most prominent patterns of positive PDO—highs over western North America and lows in the Gulf of Alaska. Also, note its similarity to the PNA pattern. Data and software for the figure obtained from the NCEP/NCAR Reanalysis Project (Kalnay *et al.* 1996). (*c*) Spring–summer PDO index obtained from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO; http://tao.atmos.washington.edu/). Note the regime shifts in 1924, 1947 and 1976/1977 (arrows).

Table 1. (*a*) Correlations between the 7-year high- and low-pass filtered fire–climate indices and the summer Arctic Oscillation, spring–summer PDO and winter El Niño Southern Oscillation indices for the period 1959–1999 (from table 2 in Macias Fauria & Johnson 2006). Fire–climate indices were obtained from the dominant upper air Northern Hemisphere height anomaly patterns during large fire events over several regions in the boreal forest of North America. Type 1 (2) fire–climate indices are positively (negatively) correlated with PDO at low frequencies and with ENSO at high frequencies. Type 3 (4) fire–climate indices are positively (negatively) correlated with AO at high frequencies. Significances were computed using a Monte–Carlo significance test, which generated 1000 pairs of series with the same autoregressive structure as the original series; $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$. (*b*) Correlations between total area burned in Canada and spring–summer PDO for the period 1918–2005. Filtered series and significances were computed as in *a*.

(*a*)	period 1959–1999	PDO spring–summer	Niño three winter
high-pass series	type 1	0.27^{*}	0.76^{***}
	type 2	-0.25^{*}	-0.74^{***}
low-pass series	type 1	0.72^{***}	0.19
	type 2	-0.73^{***}	-0.19
	period 1959–1999	AO summer	
high-pass series	type 3	0.84^{***}	
	type 4	-0.82^{***}	
low-pass series	type 3	0.24	
	type 4	-0.35	
(*b*)	period 1918–2005	PDO spring–summer	
area burned in Canada	unfiltered series	0.21^{*}	
	high-pass series	-0.06	
	low-pass series	0.62^{**}	

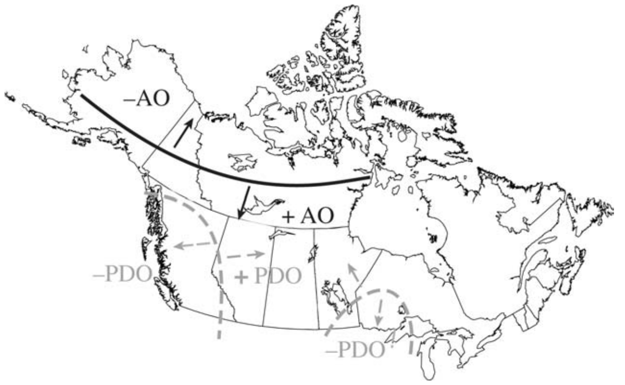

Figure 7. The geographical extent of PDO/ENSO and AO influences on large lightning fires during 1959–1999 in the North American boreal forest. Figure is based on results presented in Macias Fauria & Johnson (2006).

Thus, the increase in area burned for most of Canada in the last few decades is related to (i) a persistent positive PDO phase since 1976–1977 (figure 6) and (ii) the occurrence of positive AO situations, especially in the late 1980s and 1990s (figure 5). These conditions favoured weather prone to large fire occurrence over much of the boreal forest in North America. Neither of these two factors favoured a large area burned in British Columbia and only one (the positive phase of the PDO) favoured a large area burned in Alaska.

Using the longer (starting in 1918) area burned annual totals for Canada (Van Wagner 1988, 1991; figure 8), the link between the PDO and variability in area burned showed large and statistically significant correlations, especially (but not only) at decadal frequencies (Macias Fauria & Johnson 2006; figure 8; table 1). This relation was significant despite the probable underestimation of total area burned in the early part of the record due to a lack of data from the northern territories in Canada. Other studies (Girardin *et al.* 2006*a*; Skinner *et al.* 2006) have also pointed to the PDO as a major large-scale climatic pattern affecting large fires in the North American boreal forest. Skinner *et al.* (2006) found the summer severity rating index (cf. Van Wagner 1987) in the Canadian boreal forest to be related to global wintertime SSTs, in particular, to (i) a long-term increase in Southern Hemisphere SST, which they related to global warming, (ii) the Atlantic Multi-decadal Oscillation (AMO; Delworth & Mann 2000; Kerr 2000) and (iii) the ENSO/PDO.

In conclusion, the area burned in the boreal forest of North America was explained as a function of large-scale climatic patterns that have been operating during the twentieth century and that are linked to the occurrence and distribution over the continent of mid-tropospheric height anomalies.

3. PAST FIRE ACTIVITY

(a) *Fire frequency studies*

Apart from historic fire records, we can explore past fire frequency by a time-since-last-fire map of a study area (figure 9) and by reconstructing fire frequency from the time-since-fire (or survivorship) distribution (e.g. Johnson & Van Wagner 1985; Johnson & Gutsell 1994). The time-since-fire distributions (figure 10*a*) have generally been found to fit a negative exponential curve $A(t)=\mathrm{e}^{-(t/b)}$, in which $A(t)$ is the survivorship distribution; t is the time since last fire; and b is the fire cycle, defined as the time required to burn an area equal in size to the study area. The average fire frequency is defined as $1/b$. A negative exponential distribution implies that the hazard of burning for a given stand is time independent; that is, the age of the stand does not increase or decrease the probability of a fire occurring (if fuel accumulates with stand age it does not increase the probability of fire in the boreal forest).

The time-since-fire distributions are generally mixed distributions (figure 10*b*). This is seen by the changes in slope when the survivorship distributions are plotted on semi-log scale (for methods of separating these mixed distributions, see Reed 1997, 1998, 2000, 2001; Reed *et al.* 1998; Reed & Johnson 1999). All fire frequency studies in the boreal forest have shown mixed distributions that imply changes in

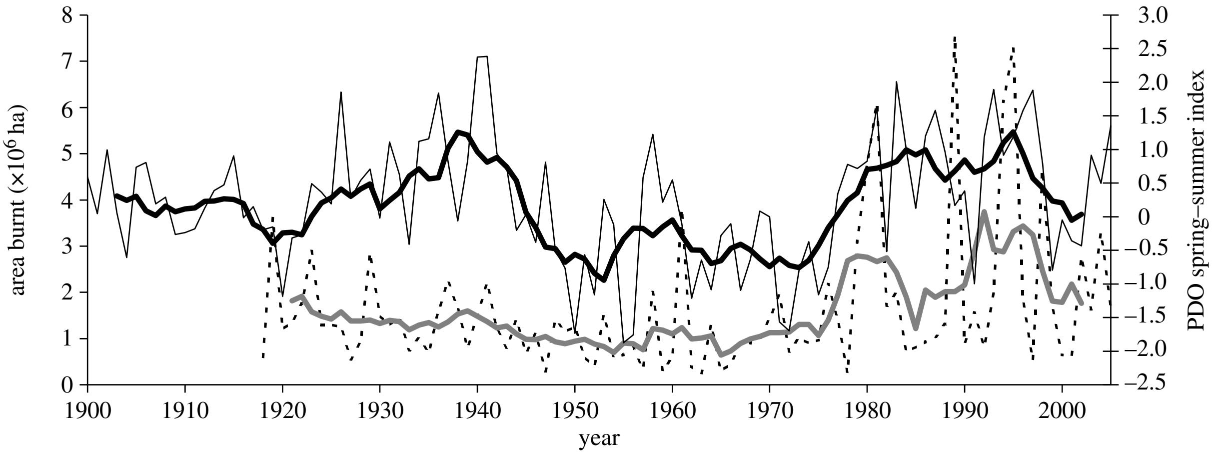

Figure 8. Forested area burned in Canada, 1918–2005 (dashed line); spring–summer PDO index, 1900–2005 (continuous line). Thick lines represent the 7-year running means in order to highlight low frequency variability (black, PDO; grey, area burned). Note the overall high similarity between both series at low frequencies.

the fire frequency. Most of these studies have remarkably synchronous changes in fire frequency over vast areas (Masters 1990; Bergeron 1991; Johnson & Larsen 1991; Johnson & Miyanishi 1991; Reed 2000; Weir *et al.* 2000; Bergeron *et al.* 2004). The general pattern in all of these reports is that the fire cycle used to be much shorter in the past three centuries and that the twentieth century has generally had longer fire cycles.

The synchronous change of fire frequencies in most of the above studies over such large spatial scales has suggested these frequency changes to be due to large-scale climate changes and not to processes acting at a stand level. The changes in fire frequency in the 1700s and 1800s have been attributed to changes in global atmospheric circulation during the Little Ice Age (e.g. Johnson & Larsen 1991; Bergeron & Archambault 1993). Fire cycles were generally shorter during the Little Ice Age, which could be the result of more frequent occurrences of high-pressure systems over northern North America (Bergeron & Archambault 1993) than during the twentieth century.

The suggested change towards longer fire cycles in the mid-nineteenth century in the North American boreal forest (e.g. Masters 1990; Larsen 1997; Reed *et al.* 1998; Flannigan *et al.* 1998; Johnson *et al.* 1999; Bergeron *et al.* 2001; Lesieur *et al.* 2002) could be linked to a shift from reduced to enhanced PDO/ENSO activity (Swetnam & Betancourt 1990; Biondi *et al.* 2001). From *ca* 1790 to the mid-nineteenth century, the frequency and strength of ENSO switching are thought to have weakened (Anderson *et al.* 1992; Cleaveland *et al.* 1992). The PDO is also reported to have had a weak decadal variability during the eighteenth and early nineteenth centuries (Biondi *et al.* 2001; Gedalof *et al.* 2002; MacDonald & Case 2005). Taylor & Beaty (2005) proposed that during that period decadal scale relationships between the PDO and ENSO broke down. This would imply a different climate in the boreal forest over that period, with different atmosphere or atmosphere–ocean circulation patterns operating and, therefore, with a different frequency of occurrence and probably location of fire-prone summer blocking highs.

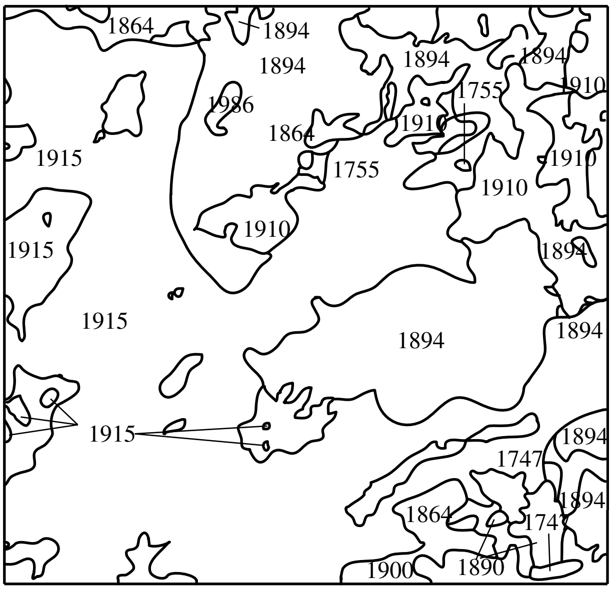

Figure 9. Small portion of the time-since-fire map of Prince Albert National Park (Saskatchewan, Canada), corresponding to fig. 3 of Johnson *et al.* (1998; source: J. M. H. Weir).

Thus, fire frequency is expected to change in a constantly changing climate (Johnson *et al.* 1998). In general, and consistent with a predicted increase in total area burned in the boreal forest of North America, fire frequency has been predicted to increase in a global change scenario (e.g. Kasischke *et al.* 1995; Flannigan *et al.* 2001, 2005); thus, the mean age of the forest as a whole is predicted to decrease. However, some reports have suggested fire frequency decreases in parts of eastern Canada associated with an increase in precipitation (Flannigan *et al.* 1998, 2001). Although the frequency of mid-tropospheric blocking highs is the causal mechanism for large fires to occur, none of these predictions has been based on such parameters.

Given the changing climate and the consequent changes in fire regimes over the last several centuries, it is impossible to talk about a 'natural fire regime' in any part of the boreal and subalpine forests of Canada and Alaska. Also, owing to this changing fire frequency, we cannot talk about a system in equilibrium, climax or

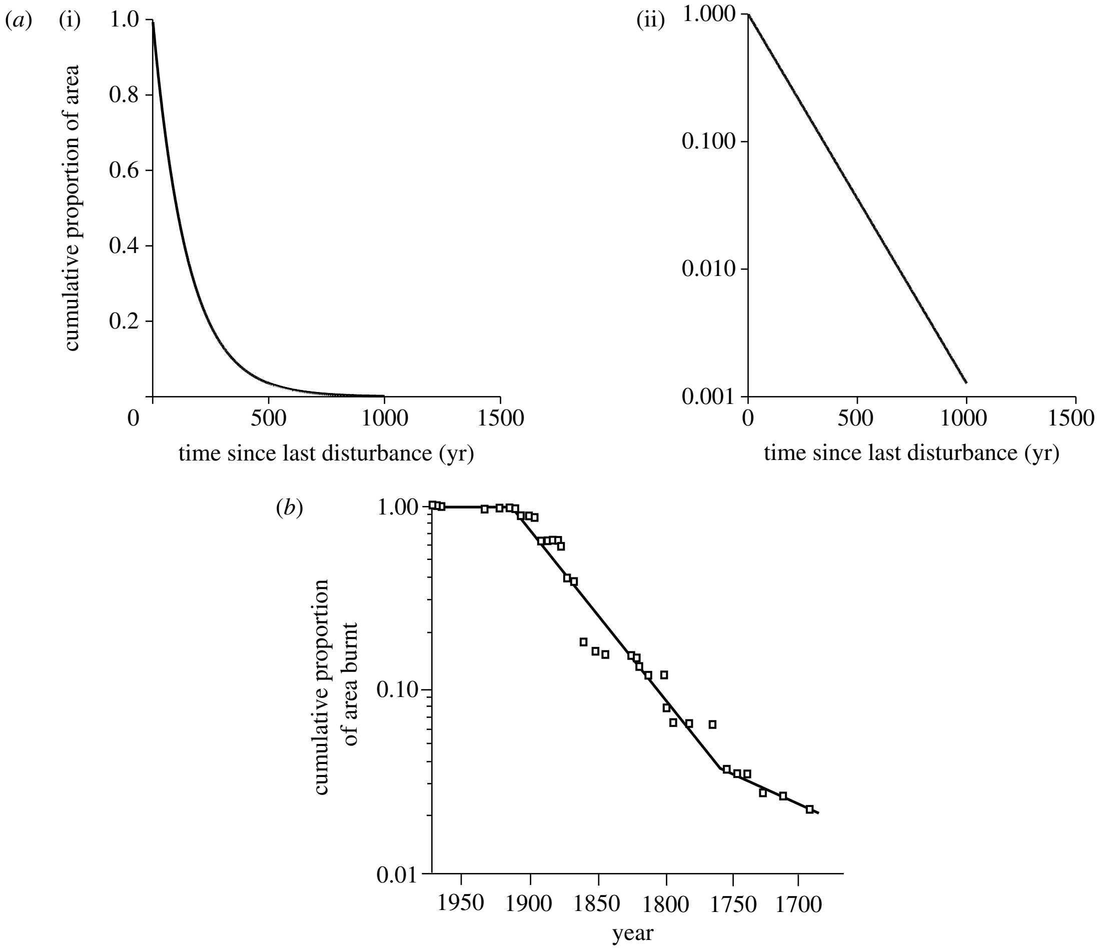

Figure 10. (*a*(i)) Example of exponential curve found to fit best most time-since-fire distributions (survivorship). $A(t)=e^{-(t/b)}$, in which $A(t)$ is the survivorship distribution; t is the time since last fire; and b is the fire cycle, defined as the time required to burn an area equal in size to the study area. It starts with the landscape unburned and describes the proportion remaining at different ages. (*a*(ii)) Semi-log time-since-fire distribution showing a straight line. (*b*) Time-since-fire distribution for the Boundary Waters Canoe Area (source: Heinselman 1973) indicating two changes in fire frequency (i.e. mixed distributions).

stasis. Thus, there is no single ‘natural’ fire cycle for any part of the boreal forest. Instead, the forested landscape mosaic is a reflection of a dynamic fire cycle and carries the memory of different past fire cycles (Johnson *et al.* 1998).

(b) *Palaeoecological studies*

Palaeoecological studies using lake sediments, macrofossils and ice cores provide information on fire activity and climate conditions during the past millennia and suggest changes in large-scale climatic patterns that relate to past fires.

In a study of diatoms from lake sediments from the northern prairies of North America (Laird *et al.* 2003), abrupt changes in aridity were found, indicating that shifts in drought regimes on a decadal to multicentennial scale have been a common feature of this region for at least the last two millennia. Regardless of the exact timing of these shifts or the direction of these changes, the persistent abrupt nature of these events represents a scale of variation that is not yet well understood, but probably is related to changes in the shape and location of the jet stream and associated storm tracks (Laird *et al.* 2003). Schindler & Donahue (2006) found that the period since European settlement appears to have been the wettest century of the past two millennia in the western Canadian Prairie Provinces. The frequent, long periods of drought that characterized the last two millennia were largely absent in the twentieth century.

Likewise, in several studies using tree rings and lake sediments, Sauchyn *et al.* (2002) found that the climate of the twentieth century in the Canadian Plains was anomalous in terms of drought, as proxy data recorded an abrupt amelioration of climatic conditions near the start of the instrumental record period. While drought was frequent in the twentieth century, it tended to be of shorter duration than during past centuries. An abrupt shift in climatic variability from centennial to decadal scale was identified around the mid-nineteenth century (Sauchyn *et al.* 2003).

Using a *ca* 3100-year oxygen isotopic ($\delta^{18}O$) composition record from northern Minnesota, Tian *et al.* (2006) reported that drought events of greater magnitude than the aridity extremes of the twentieth century were not uncommon during the Late Holocene and were strongly related to the PDO. They also noted that approximately 90% of the drought variability values during the last three millennia were greater than in the twentieth century. An ice core time series from Mt Logan (Yukon, Canada) shows a shift in climate after the mid-nineteenth century with increased snow accumulation, paralleled by an increasing trend in temperature in northwestern North America that is associated with secular trends in the PDO (Moore *et al.* 2002). All such findings are in agreement with the general decrease in fire frequency in the North American boreal forest since the mid-nineteenth century reported in §3*a* of this paper.

Lake sediments on the west slope of the Canadian Rocky Mountains show highest fire frequencies during the thermal optimum in the Mid-Holocene and lower ones in the later cooler part of the Holocene, together with changes in vegetation composition (Hallett & Hills 2000). Lake sediments in Alaska show variable fire cycles at centennial scales linked to changes in climate and in species composition during the Holocene (Anderson *et al.* 2006), with longer fire cycles in the Late Holocene under a wetter climate.

Payette & Gagnon (1985) and Payette *et al.* (1989) proposed that fire, combined with cooler climate and the consequent poor conditions for germination in northern Québec during the Late Holocene, caused a shift from closed-canopy forest to the patchy distribution of forest stands which characterizes the modern north-eastern Canadian forest tundra. Such a mechanism was proposed to have worked in periods as recent as the large fire years of the 1950s (Sirois & Payette 1991). In a study of pollen and charcoal analysis in Québec, Carcaillet *et al.* (2001) found that thermal optima in the region were associated with moist climate and reduced fires, whereas colder conditions brought abundant north-western dry air masses that favoured shorter fire cycles. Under such conditions, they proposed that an eventual global warming would probably be associated with increased moisture in the area and, thus, with a less severe fire regime.

The results of these palaeoecological studies portray a constantly changing climate and environment at all time scales from interannual to centennial. Moreover, these studies document an important shift in the mid-nineteenth century, associated with moister climatic conditions that were possibly related to changes in the ENSO/PDO system, which affected fire frequencies all across the boreal forest of North America. Thus, these studies suggest that increases in temperature do not necessarily produce more fire activity, as seen in major fire activity during periods of the Little Ice Age.

The relationship between climate, fire frequency and vegetation composition is complex. Climate change modifies the fire frequency that, together with climate change itself, enhances shifts in vegetation composition. Vegetation composition can, in turn, enhance changes in fire frequency through changes from open to closed canopy or vice versa. Thus, these three parameters are intimately linked.

4. DISCUSSION AND CONCLUSIONS

Changes in area burned due to the current global warming need to be linked to changes in the occurrence of blocking highs during the fire season. The dynamics of large-scale climatic patterns (ENSO/PDO and/or AO) are important in controlling such frequencies and are thus strongly related to the area burned in the North American boreal forest (Macias Fauria & Johnson 2006; Skinner *et al.* 2006). Studies on the influence of anthropogenic climate change on the AO and PDO remain inconclusive: while there is some evidence that the increasing greenhouse gases will lead to a more positive AO (Shindell *et al.* 1999; Hoerling *et al.* 2001), observations and climate models cannot provide a definitive answer on this yet, and have failed to predict the shift of the AO to a neutral state since the late 1990s (e.g. Overland & Wang 2005). As for the PDO, too little is known so far about its mechanisms to state whether its dynamics are being affected by global warming (e.g. Mantua & Hare 2002).

These teleconnections operate at different time scales from interannual to centennial. Strong climatic shifts in the past centuries in northern North America (e.g. Laird *et al.* 2003) have been associated with changes in the strength and coupling of the PDO/ENSO climatic system in this area (e.g. Hessl *et al.* 2004; Tian *et al.* 2006).

Fire reports, time-since-fire map fire frequency studies and palaeoecological studies report past changes in fire frequency. Moreover, many studies have noted changes of the dominant pattern of fire variability and fire–climate relationships from centennial/decadal to interannual time scales, both in the boreal forest of North America (Girardin *et al.* 2006*a*,*b*) and in other areas of North America (Taylor & Beaty 2005).

Here, we propose a simple idea of how such changes in the temporal scale of the fire–climate relationships might take place (figure 11). Within the centennial/decadal climate variability, climate remains under a very dry regime for long periods (e.g. Sauchyn *et al.* 2002, 2003; Laird *et al.* 2003; Schindler & Donahue 2006). Under such conditions, it is logical to think that persistent blocking highs are the usual climate pattern over the area. Thus, fire-prone conditions happen very frequently and year-to-year variability is not very important: decadal to centennial variability dominates fire–climate relationships. On the other hand, under periods with a more variable climate or with a climate 'locked' into a moist period, large-area-burned conditions only occur in particular years or clusters of years of extreme fire weather, and thus interannual to decadal variability is the dominant feature in the fire–climate relationships.

It is important to remember that for large fire occurrence in the closed boreal forest, 10–15 days of persistent drought are needed to efficiently dry the fuel, followed by the occurrence of lightning (e.g. Nash & Johnson 1996). Thus, when referring to centennial, decadal and even interannual links between fire and climate, we refer to the frequency of occurrence of persistent blocking highs (i.e. changes in the probability of a given fire-prone synoptic-scale atmospheric arrangement to occur) and not to a generally dry or wet fuel over periods of years to centuries. Lightning is assumed to be abundant enough in most areas to not be limiting.

Most studies on fire frequency in the boreal forest of North America identify a change towards longer frequencies during the mid-nineteenth century, which has been attributed to climatic change (Masters 1990; Bergeron 1991; Johnson & Larsen 1991; Johnson & Miyanishi 1991; Reed 2000; Weir *et al.* 2000; Bergeron *et al.* 2004). Girardin *et al.* (2004) suggested that, associated with a northward displacement of the jet stream, subtropical Atlantic air masses have penetrated

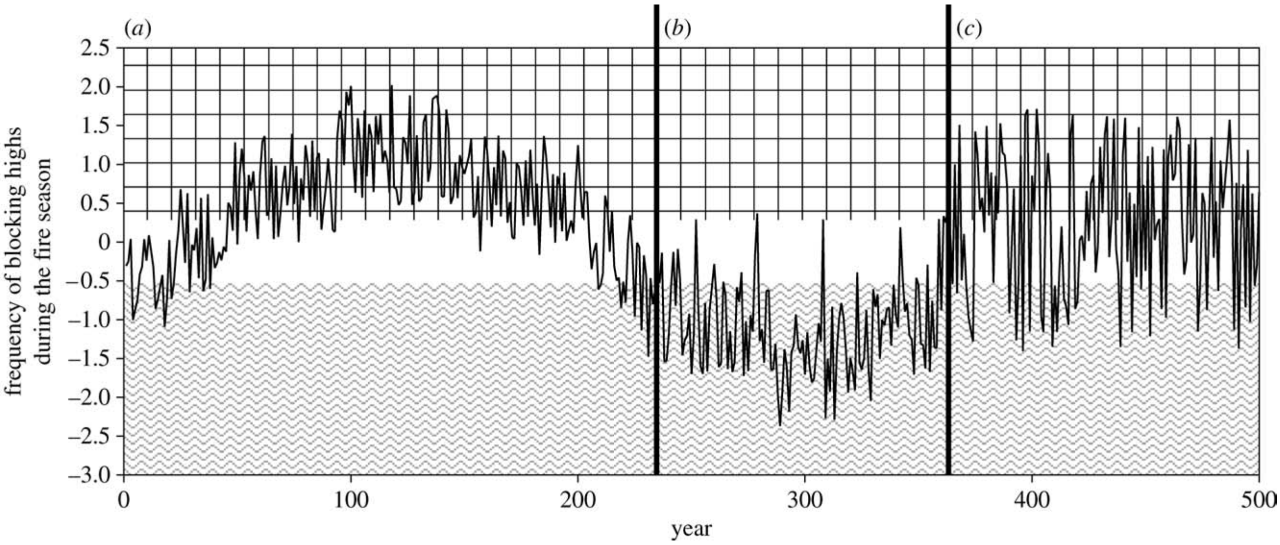

Figure 11. Plot showing an idealized climate variation over time. The y-axis represents the frequency of mid-tropospheric blocking highs during the fire season (i.e. fire hazard); large fire years are expected in the squared area, whereas low fire activity is expected in the waved area. During period (*a*), the climate remains locked in a dry phase and large fire weather occurs very frequently; decadal to centennial scales in the fire–climate relationships are expected. During period (*b*), the climate remains locked in a wet phase and large fire years occur very infrequently; however, in period (*c*), the climate enters a highly variable state and both wet and dry years occur. In periods (*b*) and (*c*), interannual climate variation is expected to be the most prominent source of large fire variability.

more frequently in Québec during this period, causing a moister climate and thus less fires. Laird *et al.* (2003) also proposed jet stream displacement to be associated with major climate shifts in more western areas of the continent. Changes in the temporal scale of fire–climate relationships have also been reported during this time (e.g. Girardin *et al.* 2006*a*,*b*). The period starting in the second half of the nineteenth century up to the present has been one of generally wet conditions and high interannual climatic variability, especially in eastern Canada but also in western Canada and Alaska. The centuries before this appear to have had more constantly fire-prone conditions (prolonged droughts) with a decadal to centennial coupling between fire and climate. The boreal forest during this period often had a younger landscape age mosaic and a different pattern of species composition than in recent centuries (e.g. Ritchie & Yarranton 1978; Lynch *et al.* 2004).

The last century and a half has thus seen fewer fires than before and a significant and generalized increase in temperatures marking the end of the Little Ice Age. That is, there is an unclear relationship between warmer temperatures and increased values of area burned. Both the Little Ice Age (*ca* AD 1500–1850) and the Medieval Warm Period (*ca* 1100–1400) showed great variability of arid and wet periods (Luckman 2000; Tian *et al.* 2006), with variable associated fire regimes. Johnson *et al.* (1990), Johnson & Larsen (1991), Reed (2000) and Weir *et al.* (2000) found changes in fire frequency within the Little Ice Age. Thus, a warmer world need not necessarily be considered a world with more fire activity in the boreal forest of North America.

It is important to clearly distinguish between a warmer world and the frequency of droughts; these two climate characteristics have occurred simultaneously at some periods but are not intrinsically related. Thus, there is no reason to predict higher values of area burned in a warmer world based solely on an increase in temperature (Flannigan & Harrington 1988; Flannigan *et al.* 1998; Bergeron *et al.* 2001).

Inter-regime climate fluctuations represent a substantial portion of the climate variability in North America, largely affected by the PDO/ENSO regime fluctuations (e.g. Tian *et al.* 2006). Some studies have hypothesized the possibility of such centennial, large spatial- and temporal-scale droughts reoccurring as a result of climate change (e.g. Schindler & Donahue 2006) or even as a part of normal climate variability (e.g. Laird *et al.* 2003). So far, there is no reason to think that such conditions should not come back. As stated above, such climatic conditions would represent a completely different set of fire–climate relationships and change the average age of the forest and its species composition.

Finally, most climatological studies on teleconnection patterns in the Northern Hemisphere are based on the cold season (e.g. Wallace & Gutzler 1981; Zhang *et al.* 1997; Thompson & Wallace 2001; Mantua & Hare 2002). Some recent studies have focused on seasons other than winter for the study of the AO and NAO teleconnections using novel methods (e.g. Portis *et al.* 2001; Ogi *et al.* 2004). Given that many biological processes take place during summer, there is a clear need for more research on the relationships and mechanisms between teleconnections and climate during the warm season in the Northern Hemisphere.

REFERENCES

Alexander, M. E., Janz, B. & Quintilio, D. 1983 Analysis of extreme wildfire behaviour in east-central Alberta: a case study. In *Seventh Conf. on Fire and Forest Meteorology, 25–28 April 1983, Fort Collins, Colorado*, pp 38–46. Boston, MA: American Meteorological Society.

Anderson, R. Y., Lindesay, J. & Parker, D. 1992 Long-term changes in the frequency of occurrence of El Niño events. In *El Niño: historical and paleoclimatic aspects of the Southern*

Oscillation (eds H. F. Diaz & V. Markgraf), pp. 193–200. Cambridge, UK: Cambridge University Press.

Anderson, R. S., Hallett, D. J., Berg, E., Jass, R. B., Toney, J. L., de Fontaine, C. S. & DeVolder, A. 2006 Holocene development of boreal forests and fire regimes on the Kenai Lowlands of Alaska. *Holocene* **16**, 791–803. (doi:10.1191/0959683606hl901ft)

Bergeron, Y. 1991 The influence of island and mainland lakeshore landscapes on boreal forest regimes. *Ecology* **72**, 1980–1992. (doi:10.2307/1941553)

Bergeron, Y. & Archambault, S. 1993 Decrease of forest fires in Quebec's southern boreal zone and its relation to global warming since the 'Little Ice Age'. *Holocene* **3**, 255–259.

Bergeron, Y. & Brisson, J. 1990 Fire regime in red pine stands at the northern limit of the species' range. *Ecology* **71**, 1352–1364. (doi:10.2307/1938272)

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P. & Lesieur, D. 2001 Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. *Can. J. For. Res.* **31**, 384–391. (doi:10.1139/cjfr-31-3-384)

Bergeron, Y., Gauthier, S., Flannigan, M. & Kafka, V. 2004 Fire regimes at the transition between mixedwood and coniferous boreal forest in northwestern Quebec. *Ecology* **85**, 1916–1932. (doi:10.1890/02-0716)

Bessie, W. C. & Johnson, E. A. 1995 The relative importance of fuels and weather on fire behavior in subalpine forests. *Ecology* **76**, 747–762. (doi:10.2307/1939341)

Biondi, F., Gershunov, A. & Cayan, D. R. 2001 North Pacific Decadal climate variability since 1661. *J. Clim.* **14**, 5–10. (doi:10.1175/1520-0442(2001)014<0005:NPDCVS>2.0.CO;2)

Carcaillet, C., Bergeron, Y., Richard, P. J. H., Fréchette, B., Gauthier, S. & Prairie, Y. T. 2001 Change of fire frequency in the eastern Canadian boreal forests during the Holocene: does vegetation composition or climate trigger the fire regime? *J. Ecol.* **89**, 930–946. (doi:10.1111/j.1365-2745.2001.00614.x)

Cleaveland, M. K., Cook, E. R. & Stahle, D. W. 1992 Secular variability of the Southern Oscillation detected in tree ring data from Mexico and the southern United States. In *El Niño: historical and paleoclimatic aspects of the Southern Oscillation* (eds H. F. Diaz & V. Markgraf), pp. 271–291. Cambridge, UK: Cambridge University Press.

Delworth, T. L. & Mann, M. E. 2000 Observed and simulated multidecadal variability in the Northern Hemisphere. *Clim. Dyn.* **16**, 661–676. (doi:10.1007/s00382 0000075)

Desponts, M. & Payette, S. 1993 The Holocene dynamics of jack pine at its northern range limit in Québec. *J. Ecol.* **81**, 719–727. (doi:10.2307/2261669)

Dickson, R. R. & Namias, J. 1976 North American influences on the circulation and climate of the North Atlantic sector. *Mon. Weather Rev.* **104**, 1255–1265. (doi:10.1175/1520-0493(1976)104<1255:NAIOTC>2.0.CO;2)

Flannigan, M. D. & Harrington, J. B. 1986 Synoptic weather conditions during the Porter Lake experimental fire project. *Climatol. Bull.* **20**, 19–40.

Flannigan, M. D. & Harrington, J. B. 1988 A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada (1953–1980). *J. Appl. Meteorol.* **27**, 441–452. (doi:10.1175/1520-0450(1988)027<0441:ASOTRO>2.0.CO;2)

Flannigan, M. D. & Wotton, B. M. 2001 Climate, weather, and area burned. In *Forest fires: behavior and ecological effects* (eds E. A. Johnson & K. Miyanishi), pp. 351–373. San Diego, CA: Academic Press.

Flannigan, M. D., Bergeron, Y., Engelmark, O. & Wotton, B. M. 1998 Future wildfire in circumboreal forests in relation to global warming. *J. Veg. Sci.* **9**, 469–476. (doi:10.2307/3237261)

Flannigan, M., Campbell, I., Wotton, M., Carcaillet, C., Richard, P. & Bergeron, Y. 2001 Future in Canada's boreal forest: paleoecology results and general circulation model—regional climate model simulations. *Can. J. For. Res.* **31**, 854–864. (doi:10.1139/cjfr-31-5-854)

Flannigan, M. D., Logan, K. A., Amiro, B. D., Skinner, W. R. & Stocks, B. J. 2005 Future area burned in Canada. *Clim. Change* **72**, 1–16. (doi:10.1007/s10584-005-5935-y)

Fryer, G. I. & Johnson, E. A. 1988 Reconstructing fire behavior and effects in a subalpine forest. *J. Appl. Ecol.* **25**, 1063–1072. (doi:10.2307/2403766)

Gedalof, Z., Mantua, N. J. & Peterson, D. L. 2002 A multi-century perspective of variability in the Pacific Decadal Oscillation: new insights from tree rings and coral. *Geophys. Res. Lett.* **29**, 2204. (doi:10.1029/2002GL015824)

Gershunov, A. & Barnett, T. P. 1998 Interdecadal modulation of ENSO teleconnections. *Bull. Am. Meteorol. Soc.* **79**, 2715–2726. (doi:10.1175/1520-0477(1998)079<2715:IMOET>2.0.CO;2)

Gillett, N. P., Weaver, A. J., Zwiers, F. W. & Flannigan, M. D. 2004 Detecting the effect of climate change on Canadian forest fires. *Geophys. Res. Lett.* **31**, L18211. (doi:10.1029/2004GL020876)

Girardin, M.-P., Tardif, J., Flannigan, M. D. & Bergeron, Y. 2004 Multicentury reconstruction of the Canadian Drought code from eastern Canada and its relationship with paleoclimatic indices of atmospheric circulation. *Clim. Dyn.* **23**, 99–115. (doi:10.1007/s00382-004-0417-x)

Girardin, M., Tardif, J. C., Flannigan, M. D. & Bergeron, Y. 2006*a* Synoptic-scale atmospheric circulation and boreal Canada summer drought variability of the past three centuries. *J. Clim.* **19**, 1922–1947. (doi:10.1175/JCLI3716.1)

Girardin, M., Tardif, J. C. & Flannigan, M. D. 2006*b* 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)

Hallett, D. J. & Hills, L. V. 2000 Holocene vegetation dynamics, fire history, lake level and climate change in the Kootenay Valley, southeastern British Columbia, Canada. *J. Paleolimnol.* **35**, 351–371. (doi:10.1007/s10933-005-1335-6)

Hare, S. R. 1996 Low frequency climate variability and salmon production. Ph.D. thesis, University of Washington, Seattle, WA.

Heinselman, M. L. 1973 Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. *Quat. Res.* **3**, 329–382. (doi:10.1016/0033-5894(73)90003-3)

Hess, J. C., Scott, C. A., Hufford, G. L. & Fleming, M. D. 2001 El Niño and its impact on fire weather in Alaska. *Int. J. Wildl. Fire* **10**, 1–13. (doi:10.1071/WF01007)

Hessl, A., McKenzie, D. & Schellhaas, R. 2004 Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. *Ecol. Appl.* **14**, 425–442. (doi:10.1890/03-5019)

Hoerling, M. P., Hurrell, J. W. & Xu, T. 2001 Tropical origins for recent North Atlantic climate change. *Science* **292**, 90–92. (doi:10.1126/science.1058582)

IPCC, 2001 *Climate change 2001: the scientific basis* (eds J.T. Houghton Y. Ding D.G. Griggs M. Noguer P. J. van der Linden X. Dai K. Maskell C. Johnson), Cambridge, UK: Cambridge, University Press.

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

Johnson, E. A. 1993 Wildfires in Alaska boreal forest and tundra. In *Sensitivity of Alaskan biological and social systems to climate change*. Washington, DC: Office of Technology Assessment of the U.S. Congress.

Johnson, E. A. & Fryer, G. I. 1989 Population dynamics in lodgepole pine-Engelmann spruce forests. *Ecology* **70**, 1335–1345. (doi:10.2307/1938193)

Johnson, E. A. & Gutsell, S. L. 1994 Fire frequency models, methods and interpretations. *Adv. Ecol. Res.* **25**, 239–287.

Johnson, E. A. & Larsen, C. P. S. 1991 Climatically induced change in fire frequency in the southern Canadian Rockies. *Ecology* **72**, 194–201. (doi:10.2307/1938914)

Johnson, E. A. & Miyanishi, K. 1991 Fire and population dynamics of lodgepole pine and Engelmann spruce forests in the southern Canadian Rockies. In *Coniferous forest ecology from an international perspective* (eds N. Nakagoshi & F. B. Golley), pp. 77–91. The Hague, The Netherlands: SPB Academic Publishing.

Johnson, E. A. & Van Wagner, C. E. 1985 The theory and use of two fire history models. *Can. J. For. Res.* **15**, 214–220.

Johnson, E. A. & Wowchuk, D. R. 1993 Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies. *Can. J. For. Res.* **23**, 1213–1222. (doi:10.1139/x93-153)

Johnson, E. A., Fryer, G. I. & Heathcott, M. J. 1990 The influence of man and climate on frequency of fire in the interior wet belt forest, British Columbia. *J. Ecol.* **78**, 403–412. (doi:10.2307/2261120)

Johnson, E. A., Miyanishi, K. & Weir, J. M. H. 1998 Wildfires in the western Canadian boreal forest: landscape patterns and ecosystem management. *J. Veg. Sci.* **9**, 603–610. (doi:10.2307/3237276)

Johnson, E. A., Miyanishi, K. & O'Brien, N. 1999 Long-term reconstruction of the fire season in the mixedwood boreal forest of western Canada. *Can. J. Bot.* **77**, 1185–1188. (doi:10.1139/cjb-77-8-1185)

Johnson, E. A., Miyanishi, K. & Bridge, S. R. J. 2001 Wildfire regime in the boreal forest and the idea of suppression and fuel buildup. *Conserv. Biol.* **15**, 1554–1557. (doi:10.1046/j.1523-1739.2001.01005.x)

Kalnay, E. *et al.* 1996 The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc.* **77**, 437–471. (doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2)

Kasischke, E. S., Christensen, N. L. & Stocks, B. J. 1995 Fire, global warming, and the carbon balance of boreal forests. *Ecol. Appl.* **5**, 437–451. (doi:10.2307/1942034)

Keeley, J. E. & Fotheringham, C. J. 2001 History and management of crown-fire ecosystems: a summary and response. *Conserv. Biol.* **15**, 1561–1567. (doi:10.1046/j.1523-1739.2001.t01-1-00186.x)

Kerr, R. A. 2000 A North Atlantic climate pacemaker for the centuries. *Science* **288**, 1984–1985. (doi:10.1126/science.288.5473)

Kurz, W. A. & Apps, M. J. 1999 A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecol. Appl.* **9**, 526–547. (doi:10.1890/1051-0761(1999)009[0526:AYRAOC]2.0.CO;2)

Laird, K. R., Cumming, B. F., Wunsam, S., Rusak, J. A., Oglesby, R. J., Fritz, S. C. & Leavitt, P. R. 2003 Lake sediments record large-scale shifts in moisture regimes across the northern prairies of North America during the past two millennia. *Proc. Natl Acad. Sci. USA* **100**, 2483–2488. (doi:10.1073/pnas.0530193100)

Larsen, C. P. S. 1997 Spatial and temporal variations in boreal forest fire frequency. *J. Biogeogr.* **24**, 663–673.

Lesieur, D., Gauthier, S. & Bergeron, Y. 2002 Fire frequency and vegetation dynamics for the south-central boreal forest of Quebec, Canada. *Can. J. For. Res.* **32**, 1996–2009. (doi:10.1139/X02-113)

Luckman, B. H. 2000 The Little Ice Age in the Canadian Rockies. *Geomorphology* **32**, 357–384. (doi:10.1016/S0169-555X(99)00104-X)

Lynch, J. A., Hollis, J. L. & Hu, F. S. 2004 Climatic and landscape controls of the boreal forest fire regime: Holocene records from Alaska. *J. Ecol.* **92**, 477–489. (doi:10.1111/j.0022-0477.2004.00879.x)

MacDonald, G. M. & Case, R. A. 2005 Variations in the Pacific Decadal Oscillation over the past millennium. *Geophys. Res. Lett.* **32**, L08703. (doi:10.1029/2005GL022478)

Macias Fauria, M. & Johnson, E. A. 2006 Large-scale climatic patterns control large lightning fire occurrence in Canada and Alaska forest regions. *J. Geophys. Res.* **111**, G04008. (doi:10.1029/2006JG000181)

Mantua, N. J. & Hare, S. R. 2002 The Pacific Decadal Oscillation. *J. Oceanogr.* **58**, 35–44. (doi:10.1023/A:1015820616384)

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M. & Francis, R. C. 1997 A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Am. Meteorol. Soc.* **78**, 1069–1079. (doi:10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2)

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

Minobe, S. 1997 A 50–70 year climatic oscillation over the North Pacific and North America. *Geophys. Res. Lett.* **24**, 683–686. (doi:10.1029/97GL00504)

Minobe, S. 2000 Spatio-temporal structure of the pentadecadal variability over the North Pacific. *Prog. Oceanogr.* **47**, 381–408. (doi:10.1016/S0079-6611(00)00042-2)

Moore, G. W. K., Holdsworth, G. & Alverson, K. 2002 Climate change in the North Pacific region over the past three centuries. *Nature* **240**, 401–403. (doi:10.1038/nature01229)

Namias, J. 1978 Multiple causes of the North American abnormal winter 1976–1977. *Mon. Weather Rev.* **106**, 279–295. (doi:10.1175/1520-0493(1978)106<0279:MCOTNA>2.0.CO;2)

Nash, C. H. & Johnson, E. A. 1996 Synoptic climate of lightning caused forest fires in the subalpine and boreal forests. *Can. J. For. Res.* **26**, 1859–1874.

Newark, M. J. 1975 The relationship between forest fire occurrences and 500 mb longwave ridging. *Atmosphere* **13**, 26–33.

Ogi, M., Yamazaki, K. & Tachibana, Y. 2004 The summertime annular mode in the Northern Hemisphere and its linkage to the winter mode. *J. Geophys. Res.* **109**, D20114. (doi:10.1029/2004JD004514)

Overland, J. E. & Wang, M. 2005 The Arctic climate paradox: the recent decrease of the Arctic Oscillation. *Geophys. Res. Lett.* **32**, L06701. (doi:10.1029/2004GL021752)

Payette, S. & Gagnon, R. 1985 Late Holocene deforestation and tree regeneration in the forest–tundra of Québec. *Nature* **313**, 570–572. (doi:10.1038/313570a0)

Payette, S., Morneau, C., Sirois, L. & Desponts, M. 1989 Recent fire history of the northern Québec biomes. *Ecology* **70**, 656–673. (doi:10.2307/1940217)

Portis, D. H., Walsh, J. E., El Hamly, M. & Lamb, P. J. 2001 Seasonality of the North Atlantic Oscillation. *J. Clim.* **14**, 2069–2078. (doi:10.1175/1520-0442(2001)014<2069:SOTNAO>2.0.CO;2)

Randerson, J. T. *et al.* 2006 The impact of boreal forest fire on climate warming. *Science* **314**, 1130–1132. (doi:10.1126/science.1132075)

Reed, W. J. 1997 Estimating historical forest fire frequency from time-since-fire sample data. *IMA J. Appl. Med. Biol.* **14**, 71–83. (doi:10.1093/imammb/14.1.71)

Reed, W. J. 1998 Determining changes in historical forest fire frequency from a time-since-fire map. *J. Agric. Biol. Environ. Stat.* **3**, 430–450. (doi:10.2307/1400575)

Reed, W. J. 2000 Reconstructing the history of forest fire frequency: identifying hazard rate change points using the Bayes information criterion. *Can. J. Stat.* **28**, 353–365. (doi:10.2307/3315984)

Reed, W. J. 2001 Statistical inference for historical fire frequency using the spatial mosaic. In *Forest fires: behavior and ecological effects* (eds E. A. Johnson & K. Miyanishi), pp. 419–435. San Diego, CA: Academic Press.

Reed, W. J. & Johnson, E. A. 1999 Reply—reverse cumulative standing age distributions in fire-frequency analysis. *Can. J. For. Res.* **29**, 1812–1815. (doi:10.1139/cjfr-29-11-1812)

Reed, W. J., Larsen, C. P. S., Johnson, E. A. & MacDonald, G. M. 1998 Estimation of temporal variations in historical fire frequency from time-since-fire map data. *For. Sci.* **44**, 465–475.

Ritchie, J. C. & Yarranton, G. A. 1978 The Late-Quaternary history of the boreal forest of central Canada, based on standard pollen stratigraphy and principal components analysis. *J. Ecol.* **66**, 199–212. (doi:10.2307/2259188)

Sauchyn, D. J., Barrow, E. M., Hopkinson, R. F. & Leavitt, P. R. 2002 Aridity on the Canadian Plains. *Géogr. Phys. Quat.* **56**, 247–259.

Sauchyn, D. J., Stroich, J. & Beriault, A. 2003 A paleoclimatic context for the drought of 1999–2001 in the northern Great Plains of North America. *Geogr. J.* **169**, 158–167. (doi:10.1111/1475-4959.05003)

Schindler, D. W. & Donahue, W. F. 2006 An impending water crisis in Canada's western prairie provinces. *Proc. Natl Acad. Sci. USA* **103**, 7210–7216. (doi:10.1073/pnas.0601568103)

Schroeder, M. J. *et al.* 1964 *Synoptic weather types associated with critical fire weather*. Berkeley, CA: USDA Forest Service, Pacific Southwest Forest and Range Experiment Station.

Serreze, M. C. *et al.* 2000 Observational evidence of recent change in the northern high-latitude environment. *Clim. Change* **46**, 159–207. (doi:10.1023/A:1005504031923)

Shindell, D. T., Miller, R. L., Schmidt, G. A. & Pandolfo, L. 1999 Simulation of recent northern winter climate trends by greenhouse-gas forcing. *Nature* **399**, 452–455. (doi:10.1038/20905)

Sirois, L. & Payette, S. 1991 Reduced postfire tree regeneration along a boreal forest forest–tundra transect in northern Québec. *Ecology* **72**, 619–627. (doi:10.2307/2937202)

Skinner, W. R., Stocks, B. J., Martell, D. L., Bonsal, B. & Shabbar, A. 1999 The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada. *Theor. Appl. Climatol.* **63**, 89–105. (doi:10.1007/s007040050095)

Skinner, W. R., Shabbar, E., Flannigan, M. D. & Logan, K. 2006 Large forest fires in Canada and the relationship to global sea surface temperatures. *J. Geophys. Res.* **111**, D14106. (doi:10.1029/2005JD006738)

Stocks, B. J. *et al.* 1998 Climate change and forest fire potential in Russian and Canadian boreal forests. *Clim. Change* **38**, 1–13. (doi:10.1023/A:1005306001055)

Stocks, B. J. *et al.* 2003 Large forest fires in Canada, 1959-1997. *J. Geophys. Res. Atmos.* **108**, 8149. (doi:10.1029/2001JD000484)

Street, R. B. 1989 Climate change and forest fires in Ontario. In *Proc. 10th Conf. on Fire and Forest Meteorology, 17–21 April 1989, Ottawa* (eds D. C. MacIver, H. Auld & R. Whitewood), pp. 177–182. Ottawa, Canada: Forestry Canada, Environment Canada.

Street, R. B. & Birch, E. C. 1986 Synoptic fire climatology of the Lake Athabasca—Great Slave Lake area, 1977–1982. *Clim. Bull.* **20**, 3–18.

Swetnam, T. W. & Betancourt, J. J. 1990 Fire-Southern Oscillation relations in the southwestern United States. *Science* **249**, 1018–1020. (doi:10.1126/science.249.4972.1017)

Taylor, A. H. & Beaty, R. M. 2005 Climatic influences on fire regimes in the northern Sierra Nevada mountains, Lake Tahoe Basin, Nevada, USA. *J. Biogeogr.* **32**, 425–438. (doi:10.1111/j.1365-2699.2004.01208.x)

Thompson, D. W. J. & Wallace, J. M. 1998 The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.* **25**, 1297–1300. (doi:10.1029/98GL00950)

Thompson, D. W. J. & Wallace, J. M. 2000 Annular modes in the extratropical circulation. Part I: month-to-month variability. *J. Clim.* **13**, 1000–1016. (doi:10.1175/1520-0442(2000)013<1000:AMITEC>2.0.CO;2)

Thompson, D. W. J. & Wallace, J. M. 2001 Regional climate impacts of the Northern Hemisphere annular mode. *Science* **293**, 85–89. (doi:10.1126/science.1058958)

Tian, J., Nelson, D. M. & Hu, F. S. 2006 Possible linkages of Late-Holocene drought in the North American mid-continent to Pacific Decadal Oscillation and solar activity. *Geophys. Res. Lett.* **33**, L23702. (doi:10.1029/2006GL028169)

Trenberth, K. E. & Paolino, D. A. 1981 Characteristic patterns of variability of sea-level pressure in the Northern Hemisphere. *Mon. Weather Rev.* **109**, 1169–1189. (doi:10.1175/1520-0493(1981)109<1169:CPOVOS>2.0.CO;2)

van Loon, H. & Rogers, J. C. 1978 The seesaw winter temperatures between Greenland and Northern Europe. Part I: general description. *Mon. Weather Rev.* **106**, 296–310. (doi:10.1175/1520-0493(1978)106<0296:TSIWTB>2.0.CO;2)

Van Wagner, C. E. 1987 *The development and structure of the Canadian Forest Fire weather index system*. Forestry technical report no. 35. Ottawa, Canada: Canadian Forest Service.

Van Wagner, C. E. 1988 The historical pattern of annual burned area in Canada. *Forest. Chron.* **64**, 182–185.

Van Wagner, C. E. 1991 Forest fire statistics and the timber supply. In *Canada's timber resources* (ed. D. G. Brand), Information report PI-X-101, pp. 111–118. Chalk River, Canada: Petawawa National Forestry Institute, Forestry Canada.

Wallace, J. M. & Gutzler, D. S. 1981 Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Weather Rev.* **109**, 784–812. (doi:10.1175/1520-0493(1981)109<0784:TITGHF>2.0.CO;2)

Weir, J. M. H., Johnson, E. A. & Miyanishi, K. 2000 Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada. *Ecol. Appl.* **10**, 1162–1177. (doi:10.1890/1051-0761(2000)010[1162:FFATSA]2.0.CO;2)

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

Zhang, Y., Wallace, J. M. & Battisti, D. S. 1997 ENSO-like interdecadal variability: 1900–93. *J. Clim.* **10**, 1004–1020. (doi:10.1175/1520-0442(1997)010<1004:ELIV>2.0.CO;2)