The association between Northern Hemisphere climate patterns and interannual variability in Canadian wildfire activity

J.L. Beverly, M.D. Flannigan, B.J. Stocks, and P. Bothwell

Abstract: Wildfire impacts on ecological and socioeconomic systems are regulated, in part, by climate. Association between hemispheric-scale climate patterns and annual wildfire activity can be obscured by local factors that also control the initiation and spread of fires. Vegetation, topography, and fire suppression can be expected to influence conventional measures of annual wildfire activity such as area burned, effectively concealing evidence of broad-scale climate influences. This study investigates alternatives to area-burned statistics for quantifying annual wildfire activity in Canada in relation to Northern Hemisphere climate variability represented by the Atlantic Multidecadal Oscillation (AMO). We depart from conventional approaches by including socioeconomic measures of wildfire activity and by assessing spatially referenced wildfire data over units of observation chosen explicitly to diminish variability caused by factors unrelated to broad-scale climate. Our data-centred approach, combined with linear regression modelling, revealed that the AMO was positively correlated with national time series of very large fires (≥10 000 ha), wildfire-related evacuations, and fire suppression expenditures over the period 1975–2007. The AMO and wildfire activity were most closely coupled during a period of predominantly positive-phase Arctic Oscillation (AO) and Pacific Decadal Oscillation (PDO) between 1989 and 2001. Positive correlation between maximum evacuation wind speed and the AMO suggests that wind may be a causal factor in the AMO–wildfire relationship.

Résumé : Les impacts des feux de forêt sur les systèmes écologiques et socio-économiques sont déterminés en partie par le climat. La relation entre les patrons climatiques à l'échelle de l'hémisphère et l'activité annuelle des feux de forêt peut être embrouillée par des facteurs locaux qui régissent également l'initiation et la propagation des feux. La végétation, la topographie et la suppression du feu devraient influencer les mesures conventionnelles de l'activité annuelle des feux de forêt, telles que la superficie brûlée, dissimulant ainsi les indices de l'influence exercée par le climat à plus grande échelle. Cette étude porte sur des alternatives aux statistiques de superficies brûlées pour quantifier l'activité annuelle des feux de forêt au Canada en relation avec la variabilité du climat de l'hémisphère Nord, représentée par l'oscillation multidécennale de l'Atlantique (OMA). Nous nous démarquons des approches traditionnelles en incluant des mesures socio-économiques de l'activité des feux de forêt et en évaluant des données géoréférencées sur les feux de forêt pour des unités d'observation choisies explicitement dans le but de diminuer la variabilité due à des facteurs non reliés au climat. Notre approche centrée sur les données, combinée à la modélisation par régression linéaire, a révélé que l'OMA était positivement corrélée avec des séries temporelles nationales des très grands feux (≥10 000 ha), les évacuations reliées aux feux de forêt et les coûts de suppression du feu au cours de la période 1975–2007. L'OMA et l'activité des feux de forêt étaient le plus étroitement reliées durant une période où l'oscillation arctique (OA) et l'oscillation décennale du Pacifique (ODP) ont connu une phase essentiellement positive, entre 1989 et 2001. La corrélation positive entre la vitesse maximale du vent qui justifie une évacuation et l'AMO indique que le vent pourrait être responsable de la relation entre l'OMA et les feux de forêt.

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Introduction

The impact of wildfires on ecological and socioeconomic systems in any given year will be influenced, in part, by broad-scale climate patterns. In Canada, interannual variability in wildfire activity is extreme. Over the period 1980–2007, annual area burned ranged from well under a million hectares to over seven million (National Forestry Database 2009), and the annual number of people evacuated due to wildfire ranged from just 40 individuals to over 50 000 (Beverly and Bothwell 2011). In recent decades, annual area burned has increased in Canada (Podur et al. 2002; Stocks et al. 2002), often coinciding with peaks in wildfire-related evacuation activity as in 1989, 1995, and 1998.

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Anomalous midtropospheric circulation patterns are known to produce fire ignition sources (i.e., lightning) in combination with the weather and fuel moisture conditions necessary for large fire growth in Canadian ecosystems (Flannigan and Harrington 1986; Johnson and Wowchuk 1993; Skinner et al. 1999, 2002). These circulation patterns, and resulting wildfire activity, have been linked to broad-scale climate teleconnections related to atmosphere–ocean interactions (Skinner et al. 1999, 2002, 2006; Girardin et al. 2006; Macias Fauria and Johnson 2006, 2008; Meyn et al. 2009; Wang et al. 2010).

The strength of association between broad-scale climate patterns and annual wildfire activity, typically represented by area-burned statistics, is often weak due to a variety of other factors that also control the initiation and spread of fires. Fire occurrence and fire size will be influenced by a wide variety of local phenomena such as storm track and lightning-strike position, recent and instantaneous weather conditions, microscale variations in forest fuel arrangement, composition, and moisture content, and the composition and structure of landscape features that can either constrain or support fire spread, including topography, prior disturbance activity, and patch structure and composition, as well as human land-use activities. In crown fire ecosystems that characterize Canada's boreal forest, it is possible for large and intense stand-replacing fires to reach extremely large sizes (~10^6 ha). If these fires are detected and suppressed while small, substantially large areas may be circumvented from the annual area-burned record. By influencing the size of individual fires, factors other than weather can effectively obscure the contribution of broad-scale climate towards the area-burned record.

This study investigates alternatives to area-burned statistics for quantifying annual wildfire activity in Canada in relation to Northern Hemisphere climate variability. Our objective is to decouple the influence of climate and local factors on wildfire activity. We depart from conventional approaches by including socioeconomic measures of wildfire activity and by aggregating spatially referenced wildfire data over units of observation chosen to diminish variability caused by factors unrelated to climate. Because our approach emphasizes informed decisions about data types and observational units as a means of addressing data limitations and revealing underlying patterns, we refer to it as data-centred.

We used the Atlantic Multidecadal Oscillation (AMO) index to represent broad-scale climate patterns in our analysis. We considered the AMO an ideal candidate for investigation because its influence on interannual variability in Canadian wildfire activity was previously unconfirmed but highly plausible. The AMO is a mode of Northerm Hemisphere climate variability (Kerr 2000) that has been increasing steadily during recent decades of increased Canadian wildfire activity. The AMO is the first-rotated empirical orthogonal function (EOF) of global sea surface temperatures (SST) from which interseasonal El Niño – Southern Oscillation (ENSO) and local trends have been removed (Enfield and Mestas-Nuñez 1999; Mestas-Nuñez and Enfield 1999). It is a long time scale oceanic phenomenon with a ~70-year period and is confined mainly to the North Atlantic Ocean but can have global effects. This Atlantic Ocean – atmosphere long-term variability may provide information about summer moisture patterns and wildfire activity in Canada.

The AMO has been linked to drought patterns in Canada and the United States (Shabbar and Skinner 2004; McCabe et al. 2004) and rainfall and river flows in the United States (Enfield et al. 2001). There is strong evidence that the AMO has played an important role in modulating summer climate conditions in North America during the 20th century (Sutton and Hodson 2005). Wildfire occurrence and synchrony in western North America is influenced by warm (positive) phases of the AMO (Brown 2006; Sibold and Veblen 2006; Collins et al. 2006; Kitzberger et al. 2007; Schoennagel et al. 2007), and the AMO has been identified as an influential variable in understanding temporal patterns of forest fire weather in Canada (Skinner et al. 2006).

Despite general indications that the AMO may be an important factor for understanding wildfire activity in Canada, the AMO was found to be unrelated to the regional fire regime when assessed over a relatively small spatial scale (e.g, Le Goff et al. 2007). Recent investigations of the impact of large-scale climatic patterns on Canadian large fire occurrence do not consider the AMO as a likely explanatory variable (e.g., Macias Fauria and Johnson 2006). The Pacific Decadal Oscillation (PDO) and Arctic Oscillation (AO) are more commonly considered climate indices of relevance to fire occurrence and area burned in Canada (e.g., Macias Fauria and Johnson 2006, 2008; Meyn et al. 2009; Wang et al. 2010).

We assess the relationship between the AMO index and four time series of wildfire activity compiled from three independent national datasets that describe ecological and socioeconomic characteristics of wildfire activity in Canada, namely, wildfire evacuation activity, fire suppression expenditures, and occurrence of very large fires. If a relationship between interannual wildfire activity and the AMO can be demonstrated, our approach may provide insight for future studies of broad-scale climate influences on ecological and socioeconomic systems.

Data

Time series describing annual wildfire activity in Canada were compiled from existing datasets that documented historical large fires, wildfire evacuations, and fire suppression expenditures. We limited our time series to recent decades in an effort to control for declining completeness of records expected for periods further in the past. Annual fire suppression expenditures for the period 1980–2000 were obtained from the National Forestry Database Program, maintained by Natural Resources Canada. Fire expenditures for the 2001–2007 period were compiled by B.J. Stocks (under contract to the Canadian Forest Service) through personal correspondence with provincial and territorial fire management agencies. Expenditure values were converted to 2007 dollars using the Consumer Price Index.

Time series of very large fires were compiled from the Canadian Large Fire Database (Stocks et al. 2002), which includes fires greater than 200 ha that occurred in Canada between 1959 and 1999. The large fire data are from provincial and territorial fire reports, which are considered incomplete during the early reporting period and across low-priority areas (e.g., Podur et al. 2002); we therefore limited our analysis to areas under intense fire protection by excluding large

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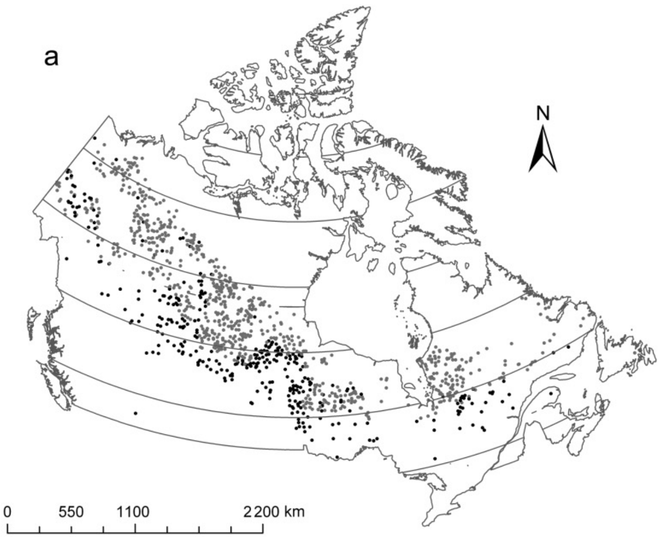
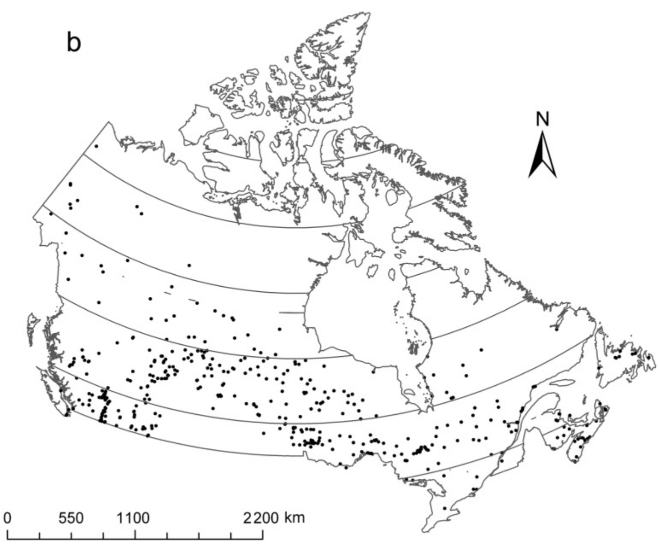
Fig. 1. Wildfire activity in Canada. (*a*) Very large lightning-caused fires (≥10 000 ha) (1975–1999). Black dots denote fires subjected to suppression. (*b*) Wildfire evacuation events (1980–2007).





fires that lacked documented suppression action and did not include data prior to 1975. Because annual numbers of large fires and the total area that they burn are influenced by factors that operate independently of large-scale climate processes, we limited our analysis to lightning-caused fires and only included fires that burned very large areas (≥10 000 ha). In total, 328 fires were included in the analysis (Fig. 1*a*). To diminish spatial and temporal variability caused by fine-scale mechanisms, we used a nominal scale (presence or absence) to summarize very large fires in a given year over broad spatial areas. We utilized latitudinal and longitudinal divisions as an arbitrary means of defining boundaries of observational units within which spatially referenced wildfire data were aggregated. Boundaries of administrative and ecological zones, which are frequently used in studies of ecological fire processes, were not considered relevant to hemispheric-scale phenomena represented by the AMO. Three units of observation were defined: 1° latitude × 1° longitudinal blocks, 1° longitudinal belts, and 1° latitudinal belts. Corresponding time series contained the number of units affected by at least one very large fire during the year.

A recently completed database documenting 547 wildfire evacuation events in Canada (Beverly and Bothwell 2011) was used to describe annual evacuation activity over the period 1980–2007 (Fig. 1*b*). These data are based primarily on media reports of evacuations, supplemented by official records from government agencies. Numbers of events were influenced by reporting conventions that sometimes involved aggregating multiple evacuations across a range of spatial scales, and annual evacuee numbers were heavily influenced by spatial variation in underlying population distribution. We therefore summarized the presence or absence of wildfire evacuation events in a given year over broad spatial areas, as was done for very large fire activity, to diminish variability in the data caused by factors unrelated to broad-scale climate interactions.

Wind speed data associated with evacuations were available for 67% of the 547 evacuation events and presented a unique opportunity to investigate potential physical mechanisms associated with broad-scale fire–climate relationships. Daily noon (local standard time) 10-m wind speed from weather station observations in the fire weather archive of the Canadian Forest Service were interpolated to each evacuation event. The wind speed value assigned to each evacuation event was the maximum daily value observed during a window that included the day of the evacuation and 5 days prior to it. Antecedent fire weather conditions were included because evacuation decisions were expected to be influenced by fire behaviour in the days leading up to the evacuation. Our evacuation wind speed time series contained the annual maximum evacuation wind speed observed in Canada for the period 1980 to 2003, during which continuous records were available.

We used the unsmoothed AMO detrended from the Kaplan SST V2 obtained from the National Oceanic and Atmospheric Administration (NOAA). Three AMO time series were computed as averages of monthly values for spring–summer (March to August), summer (May to August), and summer–fall (May to November). Averaging climate indices over seasonal periods is a common approach for assessing the influence of broad-scale climate patterns on ecological processes (e.g., Collins et al. 2006; Zhang and Delworth 2006).

Methods

Plots of the AMO and wildfire time series were used to explore possible relationships between these variables. Regression analysis was conducted using the statistical package SAS (version 9.1, SAS Institute Inc., Cary, North Carolina). We chose regression modelling because we expected our data-centred approach to expose relationships without the need for advanced statistical techniques. Regression modelling was also favoured because it is widely understood and results are easily interpreted and communicated.

Because regression models can produce significant results between time series that contain a trend but are otherwise random, detrending was used prior to analysis to remove any

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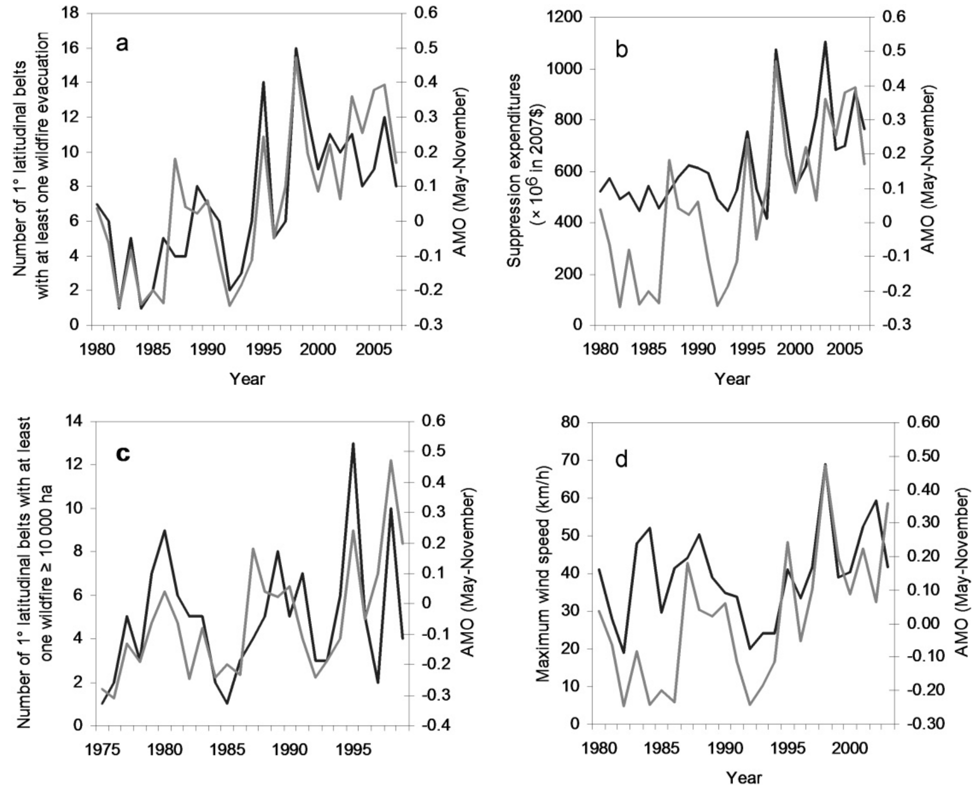
Fig. 2. Summer–fall Atlantic Multidecadal Oscillation (AMO) (shaded lines) and wildfire activity (black lines). (*a*) Wildfire evacuation activity (number of 1° latitudinal belts per year that experienced evacuations), 1980–2007. (*b*) Suppression expenditures, 1980–2007. (*c*) Very large fire activity (number of 1° latitudinal belts with at least one wildfire ≥ 10 000 ha), 1975–1999. (*d*) Maximum wind speed observed in association with evacuation events, 1980–2007.



trends in the data and avoid spurious correlations. First differencing is a common approach for inducing stationarity in time series data (Chatfield 2004) and involves subtracting from each observation the value for one year earlier. When the predictand did not have a time trend, we detrended the independent variable by estimating the trend with simple linear regression and subtracting it from the data. Correlograms and the Dickey–Fuller unit root test were used to assess stationarity following detrending. Normality of the predictand was verified with qantile–quantile (QQ) plots and the Shapiro–Wilk test.

Regression of time series data usually results in residuals that are correlated over time, thereby violating model assumptions. Independence of the regression error terms was investigated with a Durbin–Watson test for autoregressive structures. When serial autocorrelation was not present, an ordinary least square (OLS) model was estimated, otherwise PROC AUTOREG was used to estimate an autoregressive error model to adjust for serial autocorrelation in the time series based on an assumption of autoregressive structures up to two terms (Brockwell and Davis 2002). PROC AUTOREG augments the regression model with an autoregressive model for the random error. The mathematical expression for this model is

$$[1] \qquad Y_t = \alpha + \beta\chi_t + \nu_t$$

$$[2] \qquad \nu_t = -\phi_1\nu_{t-1} - \phi_2\nu_{t-2} + \varepsilon_t$$

where Y_t is the response in wildfire activity, α is the intercept, χ_t is the AMO index, ϕ_1 and ϕ_2 are the autoregressive error model parameters, ν_{t-1} and ν_{t-2} are the autoregressive error terms, and ε_t is the estimated error variance, a normal random variable with a mean of 0 and a variance of σ^2. We used backward selection to eliminate insignificant autoregressive terms ($p > 0.10$) from the model.

Estimation and results

Plots of wildfire activity time series and the AMO averaged over the summer–fall months (May–November) suggest strong associations between Canadian wildfire activity and broad-scale Northern Hemisphere climate patterns, with particularly close coupling between 1989 and 2001 (Fig. 2). All wildfire and AMO time series had significant trends over time, with the exception of maximum evacuation wind speed (1980–2003) and very large fire activity (1975–1999). For models developed with these variables, we used detrended AMO time series. For all other models, we took the first difference of both wildfire and AMO time series to induce stationarity. Following detrending, stationarity of both dependent and independent variables was assessed with correlograms and the Dickey–Fuller unit root test. No problems were found.

Models were selected for each wildfire activity time series based on the strongest correlation with an AMO time series, averaged over spring–summer, summer, or summer–fall months. For models of very large fire and evacuation activity,

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the spatial unit of observation that produced the strongest correlation with the AMO was chosen. The AMO was positively correlated with all variables used to describe annual wildfire activity (Table 1). For all four estimated regression models, correlograms of residuals revealed no significant autocorrelations, indicating that the series did not contain any dependence or nonrandomness that could be further modeled. Assumptions of linearity, normally distributed errors, homoescedaticity, and independence were diagnosed and were found to hold.

Fifty-five percent of the variance in interannual wildfire evacuation activity, measured as the number of 1° latitudinal belts affected per year in Canada (1980–2007), is attributable to the AMO averaged over the summer months (Fig. 3*a*). A substantial proportion (51%) of the variance in interannual fire suppression expenditures (1980–2007) is attributable to the AMO averaged over the spring–summer months (March to August) (Fig. 3*b*). In comparison, relatively smaller proportions of the variance in interannnual very large fire activity (38%) and maximum wind speeds associated with evacuation events (35%) were attributable to the AMO (Figs. 3*c*, 3*d*).

Annual very large fire and evacuation activity were most strongly associated with the AMO when the presence or absence of events were summarized across 1° latitudinal belts. The use of latitudinal belts and a nominal scale for describing spatially referenced wildfire activity captured the broad north–south distribution of events, while eliminating the influence of clusters, as illustrated by evacuation event maps for the years 1989, 1990, and 1998 (Fig. 4). Evacuation activity in 1989 and 1990 affected similar numbers of 1° latitudinal belts (8 and 7), but these two years had very different numbers of evacuation events (50 and 12). In comparison, 1989 and 1998 had similar numbers of events (50 and 48) but very different numbers of 1° latitudinal belts with evacuation activity (8 and 16).

Discussion

Variations in rainfall activity during positive and negative AMO phases and long-term drought conditions associated with warm (positive) phases of the AMO have been identified as a controlling mechanism on wildfire activity in some North American ecosystems (Brown 2006; Sibold and Veblen 2006; Collins et al. 2006; Kitzberger et al. 2007; Schoennagel et al. 2007). Though it is reasonable to expect an association between the AMO and wildfire activity in Canada, the close interannual variation between the AMO and all wildfire time series examined in this study is surprising and suggests that these measures of wildfire activity are particularly receptive to the underlying mechanisms that link the AMO and fire.

Wildfire-related evacuations are relatively infrequent in Canada. Persistent weather factors documented in association with these events include extended drought, hot temperatures, and extreme winds (Beverly and Bothwell 2011). Prior studies have linked the AMO to summer drought patterns in North America, but our finding of a strong positive association between the AMO and evacuation wind speeds suggests an additional underlying mechanisms by which the AMO may influence wildfire activity across Canada.

Table 1. Relationship between annual wildfire activity in Canada and the Atlantic Multidecadal Oscillation (AMO).

				Regression parameters					
Time period	n	Wildfire activity time series (Y)	AMO time series (χ)	α	β	ϕ_1	ϕ_2	ε	R^2
1980–2007	27	Δ no. of 1° latitudinal belts affected by at least one evacuation	Δ AMO (May–August)	0.029	11.329	**0.371**	0.563	5.235	0.551 (0.717), AR2
1980–2003	24	Maximum observed evacuation wind speed (km/h)	Detrended AMO (March–August)	39.425	47.003	—	—	—	0.345, OLS
1980–2007	27	Δ fire suppression expenditures (× 10^3 in 2007$)	Δ AMO (March–August)	1941	663 231	—	0.614	1.76×10^{10}	0.505 (0.623), AR2
1975–1999	25	No. of 1° latitudinal belts with at least one wildfire ≥ 10 000 ha	Detrended AMO (May–August)	4.960	10.275	—	—	—	0.376, OLS

Note: AMO, Atlantic Multidecadal Oscillation; β, ϕ_1, and ϕ_2 values are significant at the 99% confidence level unless shown in bold, which indicates 95% confidence level. Δ, first difference of the time series. Detrended time series based on removal of linear time trend. OLS, ordinary least squares regression; AR1 and AR2, first- and second-order autoregressive error models. R^2 values are regression-model R^2, with total model R^2 shown in parentheses for autoregressive error models.

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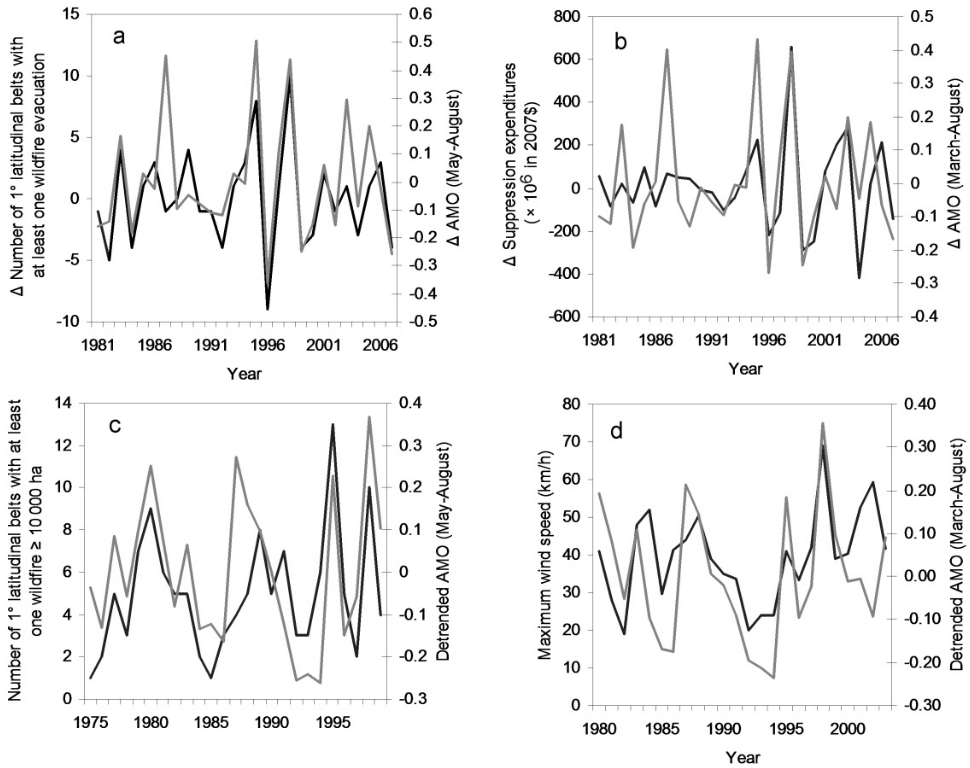
Fig. 3. Interannual variability in wildfire evacuation activity (black lines) and Atlantic Multidecadal Oscillation (AMO) (shaded lines). (*a*) First-differenced time series of wildfire evacuation activity (number of 1° latitudinal belts per year that experienced evacuations) (black line) and AMO (May–August) (shaded line). (*b*) First-differenced time series of suppression expenditures (black line) and AMO (May–November) (shaded line). (*c*) Very large fire activity (number of 1° latitudinal belts with at least one wildfire ≥ 10 000 ha) (black line) and detrended AMO (May–August) (shaded line). (*d*) Maximum wind speed observed in association with evacuations (black line) and detrended AMO (March–August) (shaded line).



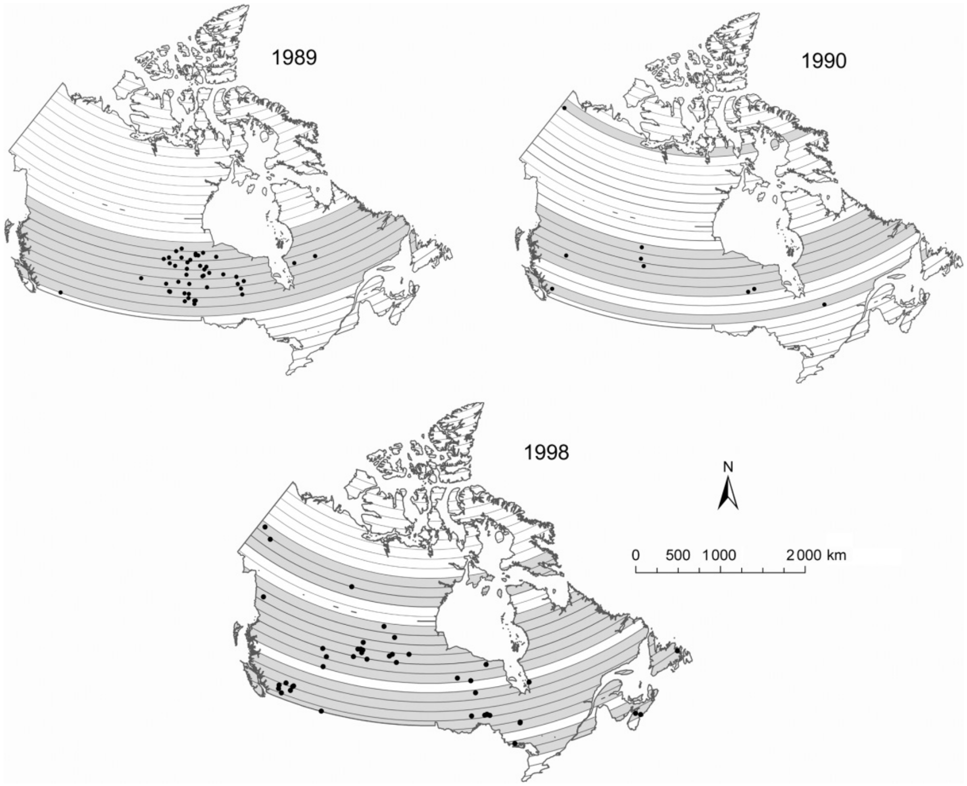
Our finding of a positive correlation between the AMO and surface wind speeds is consistent with an increased surface pressure gradient expected during AMO-positive years (cf. Sutton and Hodson 2005). The strong synchrony between the AMO and wildfire activity between 1989 and 2001 may also point to wind as an important factor. This period coincides with a predominantly positive-phase AO, and previous work has shown a positive relationship between the AO and near-surface wind speeds at locations in North America, a result that is believed to reflect enhanced westerly flow in mid- to high latitudes when the AO is positive (Klink 2007).

Extreme and unpredictable surface wind conditions can produce volatile and uncertain fire behaviour. These conditions are not a prerequisite for large fire growth, but when they do occur, they increase the likelihood that fires will escape suppression action and obtain very large sizes. Risk-averse decision-making under this irreducible uncertainty would typically involve increasing resources to ensure early fire detection, fast response times, and sufficient suppression effort. Wildfire threats to public safety and property will prompt community evacuations and increases in fire suppression efforts. All of these factors can be expected to increase expenditures and may also prompt costly resource and personnel movements within and between Canadian jurisdictions.

An understanding of the mechanisms that control interannual variability in wildfire activity, which structures forest landscapes in Canada, has fundamental ecological importance. There are also practical implications for fire management agencies in Canada. These organizations are challenged to develop strategic plans suitable for uncertain future conditions, justify extreme changes in annual expenditures from year to year, and use widely varying annual outcomes to assess the performance of largely static fire management programs that aim to minimize negative wildfire impacts. Our findings suggest that interannual variation in fire suppression expenditures in Canada in recent decades has been heavily influenced by patterns of Northern Hemisphere circulation.

We have shown a close association between the AMO and interannual variations in wildfire activity in Canada during recent decades (1975–2007). This relatively short time period coincides with a time of increasingly frequent large fire years in Canada (Podur et al. 2002; Stocks et al. 2002), a steadily increasing AMO shifting from negative to positive, and a positive-phase PDO. The AMO and wildfire activity were most closely coupled during a period of predominantly positive-phase AO and PDO between 1989 and 2001, during which time the AMO was in both negative and positive phases. We do not know the degree to which this particular combination of AMO, PDO, and AO conditions influenced our results. A positive-phase PDO and increasing AMO also occurred between approximately 1910 and 1940, which was another active period in the Canadian area-burned record (Van Wagner 1987). In contrast, the PDO shifted to a nega-

Fig. 4. Wildfire evacuation events (black dots) and corresponding 1° latitudinal belts (shaded) for the years 1989, 1990, and 1998.



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tive phase in 2008, and based on previous cycles, the current positive-phase AMO is expected to peak in 2020. Continued study of AMO–wildfire associations throughout future changes in AMO, PDO, and AO phases will be necessary to fully understand the limitations of our results.

We included socioeconomic data types in our analysis. These data types are not commonly considered in assessments of fundamental ecological processes. The AMO was most strongly associated with interannual variations in these unconventional time series of wildfire activity. Despite early applications of socioeconomic data in ecological investigations (e.g., Elton 1924), these data types are generally considered less credible than those collected expressly for ecological research. Our findings underscore the value of including socioeconomic data in studies of ecological processes.

In addition to using unconventional measures of wildfire activity, we also sought to diminish the influence of factors unrelated to broad-scale climate by choosing a spatial scale of investigation defined explicitly for that purpose. The scale of an ecological investigation is typically described in terms of spatial extent and grain and duration or temporal extent (O'Neill et al. 1986; Wiens 1989; Allen and Hoekstra 1992). Grain refers to the size of individual units of observation, and spatial extent is the overall area included in the study. The spatial extent of fire–climate studies can range from small localized study areas (e.g., Le Goff et al. 2007) to large administrative boundaries such as an entire province (e.g., Meyn et al. 2009; Wang et al. 2010). Ecological or climatic boundaries have also been used (e.g., Collins et al. 2006), but given the hemispheric scale of the AMO, we chose to assess national wildfire activity in Canada, which was the largest spatial extent across which consistent wildfire data were available. Our relatively short temporal scale (<30 years) was also largely determined by the availability of consistent and reliable wildfire data.

Spatially referenced wildfire data were assessed using a coarse grain that we expected to diminish the influence of factors unrelated to broad-scale climate patterns. We defined the boundaries of our observational units arbitrarily, using latitudinal and longitudinal divisions because we did not consider pre-existing zones such as ecological regions or administrative boundaries relevant to hemispheric-scale processes. Within these units of observation, we quantified wildfire activity on a nominal scale in an effort to further reduce the influence of factors unrelated to climate patterns. We also used an unconventional approach to compile a time series of weather observations that consisted of evacuation-related annual maximum wind speed observed at geographical locations that differed from year to year.

We expected that our data-centred approach would reveal fire–climate relationships without the need for advanced statistical techniques, and this was the case. Spatially referenced wildfire data were most strongly associated with the AMO when the presence or absence of events was summarized across 1° latitudinal belts. This observational unit captured the broad north–south distribution of events, while eliminating the influence of clusters. Although the latitudinal orientation of observational units appeared to contribute to the strength of our results, we would expect other coarse-grained units to have a similar effect on the data. The degree to which the arbitrary boundaries of latitudinal belts or any other observational unit reflects the underlying mechanisms involved merits further investigation.

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Advanced spatiotemporal statistical analysis of the wildfire time series was not the focus of our investigation. The limitations of our rudimentary statistical approach could be explored by applying spatial statistical methods and logistic regression modelling of wildfire and evacuation frequency data. Future work could also include investigating the potential confounding influence of other climate indices such as the PDO and AO.

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