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Forest fire occurrence and climate change in Canada

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Abstract. The structure and function of the boreal forest are significantly influenced by forest fires. The ignition and growth of fires depend quite strongly on weather; thus, climate change can be expected to have a considerable impact on forest fire activity and hence the structure of the boreal forest. Forest fire occurrence is an extremely important element of fire activity as it defines the load on suppression resources a fire management agency will face. We used two general circulation models (GCMs) to develop projections of future fire occurrence across Canada. While fire numbers are projected to increase across all forested regions studied, the relative increase in number of fires varies regionally. Overall across Canada, our results from the Canadian Climate Centre GCM scenarios suggest an increase in fire occurrence of 25% by 2030 and 75% by the end of the 21st century. Results projected from fire climate scenarios derived from the Hadley Centre GCM suggest fire occurrence will increase by 140% by the end of this century. These general increases in fire occurrence across Canada agree with other regional and national studies of the impacts of climate change on fire activity. Thus, in the absence of large changes to current climatic trends, significant fire regime induced changes in the boreal forest ecosystem are likely.

Introduction

Fire, which acts as a major stand renewing agent, has been an integral part of life cycles of Canada boreal forest for thousands of years. Fire influences both forest structure and function (Weber and Stocks 1998). Fire activity is strongly influenced by several factors: weather and climate, fuels, ignition agents and human activity (Countryman 1972; Johnson 1992; Swetnam 1993). Today, both lightning and human-caused fires ignite and spread across Canada's forested landscape burning on average 2.5M ha annually and current statistics (based on the last 35 years) reveal that throughout most of the country, human- and lightning-caused fires occur in roughly equal numbers (Stocks *et al*. 2002). However, examination of the records of area burned by fire typically reveals that lightning fires are the dominant cause of the majority (~80%) of the area burned in Canada due to their potential for ignition in temporal clusters and in areas far from human population (Stocks *et al*. 2002). These factors make fire suppression more difficult for two reasons. First, a large number of simultaneous ignitions can overwhelm a suppression organizations initial attack capacity. Second, fires that are located far from human population can typically evade detection for longer and when reported, can take longer to receive suppression action due to the travel time needed for suppression resources (Martell and Sun 2008).

Forest fire management in Canada is carried out by provincial and territorial agencies as well as Parks Canada (who manage fire in Canada's National Parks system). Despite the independence of these organizations, fire management activities occur in a similar manner. Fires ignited in areas where fire policies dictate they should be excluded (e.g. high value areas such as those close to human settlements or forestry operations) are aggressively attacked upon detection (called initial attack) with rapidly deployed resources. In the small percentage of cases where this initial attack is unsuccessful, resulting 'escaped fires' are generally managed for perimeter containment and extinguishment with a larger, extended mobilization of resources. The success or failure of this initial attack process has traditionally been one of the main measures of the overall success or failure of a fire management agency at achieving their goals. Large spreading fires in the boreal forest, which tend to spread as crown fires, output large amounts of energy and are difficult and often impossible to control through direct attack. The success of a fire agency in terms of limiting area burned in high value areas thus depends on finding and suppressing fires in those areas before they become large and reach a steady-state of high energy output. It is these escaped fires that grow large and lead to most of the area burned. Across Canada, one finds that 97% of area burned is caused by <3% of fires (Stocks *et al*. 2002). As such, part of an agency's daily operational activities are anticipating both the number of fires expected as well as their location, and planning resource alert levels and deployments to meet these needs.

Daily preparedness planning by the fire management agencies in Canada relies upon the Canadian Forest Fire Danger Rating System (CFFDRS) to provide an understanding of fire potential on the landscape given the weather systems affecting the region and the forest fuel types in a management area. The CFFDRS (described by Stocks *et al*. 1989) contains two major sub-systems that assist in these daily fire management planning

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decisions: a system that predicts the behavior of fire in various fuel types (Forestry Canada Fire Danger Group 1992), and a system that provides three indicators of moisture in different layers of the forest floor as well as several relative indicators of potential fire behavior (Van Wagner 1987). The outputs of this latter system, called the Canadian Forest Fire Weather Index (FWI) System, are determined based on daily observation of fire weather conditions[A] at weather stations across an agency's fire management area and are used to assist fire managers in estimating expected fire occurrence, potential fire spread and intensity.

The FWI System tracks moisture in three distinct fuel layers. The moisture content of surface litter is characterized by the Fine Fuel Moisture Content (FFMC) and is important to determining the sustainability and vigor of surface fire spread (Forestry Canada Fire Danger Group 1992; Lawson and Armitage 1997; Beverly and Wotton 2007). The moisture content of the upper portion of the organic layer in the forest floor is tracked by the Duff Moisture Code (DMC) and is important to sustainability of smouldering and fuel consumption in the forest floor (Van Wagner 1972; Frandsen 1987). The moisture content in deeper organic layers or in large pieces of woody debris on the forest floor is indicated by the Drought Code (DC) and is a useful indicator of extreme dryness and drought conditions that have the potential to make fire suppression more difficult and time-consuming. The FFMC, DMC and DC are each influenced by weather conditions to different extents. All are strongly influenced by temperature and rainfall amount; however, the FFMC is also influenced by relative humidity and wind and the DMC is additionally affected by relative humidity.

There has been significant research into the factors influencing the day-to-day variation in the numbers of fires occurring in boreal regions. These studies have shown one of the factors most strongly influencing variation in the expected number of human-caused fires is moisture content of the surface litter layer (represented by the FFMC) (e.g. Martell *et al.* 1987, 1989; Poulin-Costello 1993; Vega-Garcia *et al.* 1995; Wotton *et al.* 2003). Further studies have shown that the probability of lightning fire ignition is linked to the amount of moisture in the organic soils in the upper part of the forest floor (those soils represented by the DMC) (Flannigan and Wotton 1991; Wotton and Martell 2005). Other studies have shown that factors such as forest type also influence the number of lightning-caused fires (Krawchuk *et al.* 2006) and human influences, such as the location of population centres, roads and campgrounds also influence the absolute numbers of expected human-caused fires in a region (e.g. Vega-Garcia *et al.* 1995; Pew and Larsen 2001). However, when fire management agencies are trying to make predictions of the daily number of fires expected in a particular region, they tend to ignore fine scale variation in these static elements and focus on the dynamic changes in the moisture content of fuels which in turn have been affected by the movement of weather systems through their area of interest.

Climate change is a well recognized critical issue threatening to (and has, in many opinions, already begun to) put significant pressure on societies and ecosystems around the world. Canada is particularly sensitive to impacts of climate change due to its extensive high latitude ecosystems where changes are expected to be significant (i.e. the arctic and boreal regions). Such impacts have been widely studied (e.g. Soja *et al.* 2006; Anisimov *et al.* 2007; Field *et al.* 2007). General circulation model (GCM) scenarios show expected temperature increases across Canada in the order of 3–5°C by the end of the 21st century (Lempriere *et al.* 2008). Overall, warmer temperatures can be expected to increase evapotranspiration, lower watertables (Roulet *et al.* 1992) and decrease surface soil or fuel moisture content unless there are significant increases in precipitation. GCMs projections indicate that summer precipitation amounts and patterns across Canada are expected to change as well, with some areas seeing increased rainfall while other seeing a decrease (Flannigan *et al.* 2000). It is important to understand, however, that there is much lower confidence in GCM projections of precipitation than in projections of temperature.

Because fire activity is strongly linked with weather and fire plays such a major role in the life cycle of Canada's forest, research into the potential impacts of climate change on fire activity in Canada has been ongoing for some time (Flannigan and Van Wagner 1991; Stocks 1993; Wotton and Flannigan 1993; Bergeron and Flannigan 1995; Flannigan *et al.* 1998, 2000; Stocks *et al.* 1998). This early work focussed on the impacts of climate change on overall fire season severity using output from multiple GCMs and later, scenarios generated by Regional Climate Models (RCMs) showed that while there were some strong regional differences in Canada, overall fire seasons would increase both in length and in severity.

More recently, such climate change impacts research has focussed on predicting more physically basic (and easily understandable by the public and policy-makers) characteristics of forest fire activity such as numbers of fires and area burned. Flannigan *et al.* (2005) used correlations developed between historic area burned and various elements of fire weather (most commonly temperature) to develop projections of future area burned for the various ecozones of Canada. These results, which used the same GCM scenarios as in the current study, showed that area burned could be expected to double (from current averages) by the end of the 21st century. In a study specifically examining fire growth in the province of Alberta, Tymstra *et al.* (2007) simulated growth of fires on the landscape using weather from RCM scenarios and found that in terms of fire growth potential alone, area burned increased 30% by the end of the current century. Recently, using future GCM climates generated for western boreal North America, Balshi *et al.* (2008) projected even larger increases in area burned in the future: ~3.5 to 5.5 times current averages by the end of the 21st century.

Drever *et al.* (2008) studied large fire occurrence in the deciduous forests of western Quebec (Témiscamingue region) and suggested some increases in area burned were possible in this ecosystem. In a study of a large forested area in the province of Alberta, Krawchuk *et al.* (2009) used RCM scenarios along with previously developed relationships linking climate, fire danger and forest type to fire occurrence (Krawchuk *et al.* 2006) and projected an 80% increase in lightning fire occurrence by the end of the century. Wotton *et al.* (2003) studied the influence of climate change on human-caused fire occurrence in the province of Ontario using the daily ecoregion-based fire occurrence models

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[A] Temperature, relative humidity, 10 m open wind speed and 24-h accumulation of rainfall all recorded at 1200 hours Local Standard Time (LST).

Fig. 1. Ecoregion-based spatial units from across Canada (shaded) used to summarize weather and fire activity and develop fire occurrence models. These are based on the national framework of ecoregions of Canada and provincial political and fire management zone boundaries.

they developed. They found potential increases of 50% by the end of the 21st century. In a follow-up study, Wotton *et al.* (2005) generated scenarios of both human- and lightning-caused fire occurrence and used these with Ontario's level of protection analysis system (LEOPARDS; McAlpine and Hirsch 1999) to show that overall fire occurrence could be expected to increase by 50% by the end of the 21st century while the number of fires that escape initial attack is expected to be ~80% higher than current levels. A detailed simulation study carried out by Wotton and Stocks (2006) using LEOPARDS examined the impact of changing resource levels on managing increased fire activity. Future scenarios used in that study were quite conservative and indicated only a 15% increase in the number of fires by the year 2040. However, because increases in the number of fires push fire management agencies to the limits of their capacity more often, in that simulation, Ontario's fire management agency needed to more than double current resource capacity (i.e. fire crews, helicopters, airtankers) to maintain present levels of escape fires.

Objective

In this research, we expanded studies of forest fire occurrence carried out in Ontario to examine the impacts of climate change on fire occurrence in the rest of the forested ecoregions of Canada that have had significant forest fire activity over the past 25 years (Fig. 1). We use a previously developed and tested generalized linear model structure for fire occurrence prediction and develop simple models that allow us to predict daily fire occurrence in individual forested ecoregions across the country based on fire weather and fuel moisture information. These models of the daily expected number of fires in each ecoregion are then used with GCM scenarios to assess potential changes in annual fire occurrence with climate change. This climate change impact study focuses on provinces and territories with significant areas of forest under fire management protection. Due to unavailable information on fire report and fire weather, this study does not include the Atlantic provinces in eastern Canada and the unforested portions of the prairie provinces and territories.

Methods

Data

Datasets obtained from individual provincial fire management agencies varied somewhat in their temporal extent as well as their breakdown of fire causes into subcategories. In some cases,

Table 1. Range of years of fire occurrence and fire weather data used in the current analysis for each province and territory of Canada

Province or territory	Years of fire and weather data	Total number of fires	Total area burned (ha)
British Columbia	1980–1999	49 291	1 296 500
Alberta	1983–2004	23 697	2 420 000
Saskatchewan	1981–2005	17 697	9 434 500
Manitoba	1980–1999	11 446	9 094 700
Ontario	1980–2005	37 988	5 296 600
Quebec	1985–2000	14 960	6 070 500
Yukon	1980–1999	3760	3 097 900
Northwest Territories	1980–1999	6696	13 742 300

the length of the fire weather datasets did not match fire datasets. Where these discrepancies occurred, only the subset of the data where all information was available was used. Table 1 shows the range in years for each provincial or territorial dataset used in this analysis. While some province's digitized fire records went back many decades, we used data only from 1980 onward. We chose this cut-off to our datasets for two main reasons: (1) in modelling human-caused fires, changes in human use of the forest will take place over extended periods of time; and (2) before the advent of lightning detection systems (around 1980 in most provinces), the distinction between lightning- and human-caused fires was likely to be subject to error (Stocks *et al.* 2002).

Fire data

While fire management agencies in Canada operate in similar ways, the format and specific details of their records vary considerably. In general however, details on the ignition, spread and extinguishment of all fires detected and reported to the agency are archived as part of standard operational procedures. In recent decades, this data has been stored in digital form by each agency. This data takes the form (within every fire agency in Canada) of individual point records for each fire that occurs. Fires are spatially referenced with the latitude and longitude of the known or estimated ignition point and other attributes about the fire are based on observations by the fire management organization. For this analysis, we obtained only a subset of these agency fire records: general cause type, location (latitude, longitude), start date, report date and final area burned.

Weather station data

Each fire management agency operates their own fire weather observing network recording daily observations (at 1200 hours Local Standard Time) to estimate the fuel moisture codes and fire behavior indices of the Fire Weather Index (FWI) System. This information is in turn used for pre-suppression planning and resource deployment. Environment Canada, a federal agency responsible for monitoring and forecasting environmental conditions throughout the country, also operates weather stations throughout the country and some fire management agencies augment their own weather station networks' observations with observations from the Environment Canada network. We used weather station records both from provincial networks and Environment Canada stations (if fire weather records were not available digitally in a province for a specific period). Data obtained from these records were: temperature, relative humidity, wind speed, rainfall, FFMC, DMC, DC. Data from three other outputs of the FWI System were also obtained: Initial Spread Index (ISI), Build-Up Index (BUI) and FWI.

While some agencies have more than 200 stations in their networks, the large spatial extent of the Canadian boreal forest means there are gaps in coverage. Agencies typically spatially interpolate fuel moisture and fire behavior indices to estimate fire danger conditions between fire weather station locations. Flannigan and Wotton (1989) provide an evaluation of commonly used interpolation techniques in fire management in Canada and describe the thin-plate cubic spline method we used in this current study.

Future fire weather scenarios

Numerous GCMs have been developed by different groups around the world and several these scenarios have been selected by the Intergovernmental Panel on Climate Change (IPCC) for their recent assessments of global climate change impacts (IPCC 2001, 2007). Numerous model intercomparisons have been carried out (Covey *et al.* 2003; Meehl *et al.* 2007; Randall *et al.* 2007). For the development of future scenarios of forest fuel moisture that can be used to realistically drive models of daily expected numbers of fires, daily GCM output is needed across the area being studied. Using these extremely large datasets, data reduction and the development of daily fire weather datasets that are useful inputs to existing fuel moisture models (e.g. Van Wagner 1987) can be quite time consuming and computationally complex. In the process of data reduction and interpretation, it can also be helpful to have direct relationships with the GCM modellers responsible for original scenario development to understand assumptions and limitations in the model. We obtained our daily datasets from two well established GCMs: the Canadian Climate Centre (CCC) and from the UK's Hadley Centre (HAD). These GCMs have both been used by the international climate change impacts modelling community for well over 15 years, both used in the last three IPCC assessment reports (IPCC 1995, 2001, 2007) and provide projections consistent with other global warming projections (Covey *et al.* 2003; Meehl *et al.* 2007; Randall *et al.* 2007).

From the CCC, daily data was obtained from the first generation coupled ocean–atmosphere model (CGCM1; Flato *et al.* 2000) for three 21-year time slices spanning 1975–1995, 2020–2040 (referred to hereafter as the 2030 scenario) and 2080–2100 (referred to hereafter as 2090 scenario). This model included both greenhouse gas and sulfate aerosol forcing contributing to a 1% increase in CO_2 per year. This is similar to an A2 emission scenario used in the fourth IPCC assessment (IPCC 2007), a 'business-as-usual' scenario very commonly used in climate change impacts studies. Given that greenhouse gases have been found recently to be increasing at rates faster than this 1% per year (Raupach *et al.* 2007), we believe that for the purposes of this study, this represents a realistic 'middle of the road' emission scenario for the future. The time period 2080–2100 roughly corresponds to an equivalent $3\times CO_2$ scenario when including the net radiative effect of all the greenhouse gases. The grid spacing is $\sim 3.75°$ longitude by 3.75° latitude. Daily data from the Hadley Centre was obtained for time slices from 1975–1990 and the 2090 scenario from the HadCM3 model (Hulme *et al.* 1999). This implementation of the Hadley model, more formally known as HadCM3GGa1, contained only greenhouse gas forcing, and again output from the 2080–2099 time slice was roughly equivalent to a $3 \times CO_2$ scenario. The identical 21-year time periods from the CCC GCM could not be reproduced exactly using the HadCM3 GCM results due to lack of availability of the daily climate variables needed for the full time period. More detail on these daily datasets and their use in the development of future fire weather and fuel moisture scenarios are described in detail in previous research (Logan *et al.* 2004; Flannigan *et al.* 2005).

Daily fuel moisture observations were calculated for each GCM grid cell across Canada from the daily GCM weather streams and the FWI System for each of the future scenarios. Outputs at the GCM grid cell level were not used directly in analysis but interpolated, using thin-plate cubic splines, to the centre of each ecoregion to avoid any bias from using an individual grid cell as representative of a specific point. These ecoregions and the reasons for their use are described in the next section.

Modelling

In previous studies of forest fire occurrence (e.g. Martell *et al.* 1987, 1989; Poulin-Costello 1993; Vega-Garcia *et al.* 1995), it has been found that if occurrences are considered over small relatively homogenous areas, expected daily fire occurrence can be modelled reasonably well using the assumption that it follows a Poisson distribution. We chose to use the ecoregions of Canada as the basic spatial unit over which to summarize daily fire and weather information, following the approach of Wotton *et al.* (2003). These ecoregions, defined by the Ecological Stratification Working Group (1996), are areas with relatively uniform topography, underlying soil characteristics and forest species composition and as such, provide ideal spatial units area over which to summarize fire weather, fuel moisture and forest fire occurrence. Because each province and territory in Canada carried out fire management activities independently, ecoregions that spanned political borders were further broken down along provincial boundaries to eliminate any potential differences from province to province. Within several provinces (Saskatchewan, Manitoba, Ontario, Quebec), the area under fire management is broken up into full suppression zones and observation zones. In the former, policy states that all fires are actively suppressed. In the latter, fires are generally monitored and suppressed only if a fire threatens human values (e.g. lives and property in a northern community or infrastructure supporting northern communities). Where these fire management zones crossed an ecoregion border, we split the ecoregion along that fire management zone border to maintain a relatively homogeneous level of fire management for each unit. A map of the 'ecoregion' breakdown used in this study is in Fig. 1. Throughout the remainder of this paper, 'ecoregion' refers to these standard ecoregion units broken down by political and fire management zone boundaries.

Human- and lightning-caused fires are different in their ignition characteristics: the expected number of human-caused ignitions in a region is strongly driven by moisture content of fine surface fuels (Martell *et al.* 1987, 1989; Wotton *et al.* 2003), while lightning-caused ignitions are most strongly influenced by moisture in the organic layer where lightning ignitions can smoulder and holdover (Anderson 2002; Wotton and Martell 2005). Because of these differences, expected numbers of human- and lightning-caused fires are most effectively modelled as two distinct processes. Furthermore, fire agencies typically break down human-caused category into several major sub-classifications which we assembled (where our data provided enough information) into two distinct groups: those dominated by a significant spring season, and those showing a mid-summer peak in activity (as in Martell *et al.* 1987). Numbers of daily fires in each cause group were summarized for each ecoregions shown in Fig. 1. Daily fire weather, fuel moisture and fire behavior indices from the FWI System (both from the actual and GCM-derived fire weather streams) were interpolated to the approximate centroid of each ecoregion to provide a matching daily weather record to the fire occurrence record for the region.

Human-caused fire occurrence modelling

Previous studies have shown that expected number of human-caused fires occurring daily in a region can be reasonably modelled with a Poisson distribution (Martell *et al.* 1987, 1989; Poulin-Costello 1993; Mandallaz and Ye 1997; Wotton *et al.* 2003). In these models, moisture in the surface fuels is always a strong predictor of the mean of the Poisson distribution. The Fine Fuel Moisture Code (FFMC) output of the FWI System has been shown to be a significant and strong predictor of expected number of human-caused fires in regions of the boreal forest (Martell *et al.* 1987, 1989; Wotton *et al.* 2003). The FFMC tracks moisture in the litter fuels on the surface of the forest floor: the fuels that most directly influence the ignition and spread of a surface fire. Martell *et al.* (1987, 1989) also found an influence of moisture content in heavier fuels through the significance of the FWI System's BUI, which is functionally a weighted mean of the FWI System's DMC and DC. Wotton *et al.* (2003) explicitly examined DMC and DC and found they played a significant role in determining expected number of fires occurrence in a region.

The relationships between fire occurrence and fuel moisture (FFMC, DMC and DC) described in the preceding paragraph were included in developing the models for this study using generalized linear modelling (see McCullagh and Nelder 1989 for statistical background on generalized linear models). Using the approach of these previous fire occurrence studies, we assumed fires occurred as a Poisson process and thus chose a logarithmic link function for the dependent variable (number of fires) and the modelling assumption that residual errors would be from a Poisson distribution.

Martell *et al.* (1989) showed that human-caused fires could be grouped into two main sub-categories: those with a peak in activity in the spring and those with a peak in activity in the summer. Where our fire data included the distinction between different categories of human-caused fires, we examined the seasonal distribution of fire cause-subtype (e.g. railway, recreation) and classified each using a simple binary variable (CAUSE_GROUP: 1 for spring and 0 for causes with a summer peak). Typically, fire cause types grouped into 'spring peak' category exhibited a strong peak in fire occurrence during the month of May; fire cause types grouped into the 'summer peak' category, while some spring fire activity did occur, exhibited a strong peak during the months of July and August.

Models were developed for each province separately because of potential differences in record length and potential differences in the classification of fires into cause categories by each agency. Wotton and Beverly (2007) characterized the relationship between FFMC and actual litter moisture for a range of forest types across Canada and showed that the relationship can change with forest type as well as season in the year (i.e. spring or summer). Indeed, Wotton *et al.* (2003) found that the strength of the FFMC coefficient in their human-caused fire models changed across ecoregions with significant different forest composition. To account for coarse scale change in forest type across provinces, ecoregion was used as a categorical predictor in the model (labelled ECOREGION). In an attempt to account for Wotton and Beverly's (2007) observation that the relationships between fuel moisture and FFMC can change with forest type, an interaction term between ecoregion and FFMC was also included. Additionally, because Wotton and Beverly (2007) found that the relationship between the FFMC and actual surface litter moisture can be different between spring and summer (likely a result of forest canopy closure), a simple binary season variable (SEASON: 1 for days before 1 June; 0 for days after 1 June) was also included in the model to attempt to account for some of these differences.

A general model, using the key predictor variables identified from previous research (and described in the preceding paragraphs) was then fit in each province using the model form:

$$\begin{aligned}\ln(N_{\mathrm{HUM}}) = {} & \alpha_0 + \alpha_1 \cdot \mathrm{ECOREGION} + \alpha_2 \cdot \mathrm{FFMC} \\ & + \alpha_3 \cdot \mathrm{FFMC} \times \mathrm{ECOREGION} + \alpha_4 \cdot \mathrm{DMC} \\ & + \alpha_5 \cdot \mathrm{DC} + \alpha_6 \cdot \mathrm{CAUSE\_GROUP} \\ & + \alpha_7 \cdot \mathrm{SEASON} \end{aligned} \tag{1}$$

where N_{HUM} represents the total number of fires in an ecoregion on a particular day.

Lightning-caused occurrence modelling

Lightning fire occurrence was well correlated with level of moisture in the organic layer as indicated by the Duff Moisture Code (DMC) of the FWI System (Flannigan and Wotton 1991; Krawchuk *et al.* 2006) In fact, in the development of models for daily prediction of lightning fire occurrence, Wotton and Martell (2005) showed that DMC was an excellent indicator of the probability of having an ignition of the forest floor. Other lightning fire prediction models developed in Canada, have also taken advantage of this relationship (Kourtz and Todd 1992; Anderson 2002). Wotton (2009) described how these relationships hold across Canada as a whole. Thus, DMC was included as a key predictor in the current models. Wotton and Martell (2005) also found that the other moisture indictors of the FWI System had an influence (albeit less than DMC) on probability of ignition of a lightning fire. Thus, as in their models, FFMC and DC were included in the model form used in this study.

In this study, we did not have lightning records for the full country or period studied that would allow us to make use of the same type of models developed by Wotton and Martell (2005). Therefore, we model daily lightning fire occurrence on an ecoregion basis using the same approach as human-caused fires: Poisson regression. We included a categorical classification of daily rainfall amount as a surrogate for summertime lightning activity because lightning occurrence rate and rainfall intensity have been found to be correlated in numerous studies (e.g. Gosz *et al.* 1995; Sheridan *et al.* 1997; Tapia *et al.* 1998; Anderson 2000). In this categorization, we examined rainfall occurring on the current and previous day (to account for storms that had occurred during the previous day) and classified the total rainfall on these 2 days into a five level categorical variable (called R_{CLASS} in the model in Eqn 2)[B].

As with the human-caused fire occurrences, models were developed for each province individually to avoid any potential operational differences from province to province. In addition, to account for potential differences in the relationships between DMC and actual forest floor moisture between forest type (Lawson *et al.* 1997; Wilmore 2001; Otway *et al.* 2007), ecoregion was included as a categorical predictor (ECOREGION) along with an interaction between DMC and ecoregion. Indeed, Wotton and Martell (2005) showed that the strength of DMCs influence on probability of ignition varied between ecoregions. Previous model development and operational implementation of the model developed by Wotton and Martell (2005) found that the inclusion of a binary season predictor (delineating the spring and summer seasons) increased predictive power of the relationships[C]; thus, a simple binary season indictor (SEASON: 1 for before 1 June; 0 for after 1 June) was also added to the model, as was the case for the human-caused fire models. The general model fit in each province, which followed from the methods of Wotton and Martell (2005), had the form:

$$\begin{aligned}\ln(N_{\mathrm{LTG}}) = {} & \beta_0 + \beta_1 \cdot \mathrm{ECOREGION} + \beta_2 \cdot \mathrm{DMC} \\ & + \beta_3 \cdot \mathrm{ECOREGION} \times \mathrm{DMC} + \beta_4 \cdot \mathrm{FFMC} \\ & + \beta_5 \cdot \mathrm{DC} + \beta_6 \cdot \mathrm{SEASON} + \beta_7 \cdot R_{\mathrm{CLASS}} \end{aligned} \tag{2}$$

where N_{LTG} represents the total number of fires in an ecoregion on a particular day.

Future fire occurrence scenarios

Daily fire weather and fuel moisture values based on the future GCM scenarios from Canadian Climate Centre and the Hadley Centre were interpolated to the centroids of each ecoregion.

[B] This classification of the current and previous day's total rainfall (R_T) into categories was based on a simple analysis of rainfall associated with lightning in an ecoregion in central Alberta and Saskatchewan (ecoregion 147, the Mid-Boreal Uplands) that we believed was representative of the boreal forest, using data from 1984–2004. The goal was to make a simpler classification system for rainfall because of the strongly skewed nature of the daily rainfall distribution. The rainfall levels simply corresponded to the 25th, 50th, 75th, 90th and 95th percentiles of daily rainfall that occurred on days with lightning in this region. This new variable, R_{CLASS}, was thus classified as follows. $R_{\mathrm{CLASS}} = 0$, $RT \leq 0.3$; 1, $0.3 < R_T \leq 0.9$; 2, $0.9 < R_T \leq 2.3$; 3, $2.3 < R_T \leq 4.8$; 4, $4.8 < R_T \leq 7.3$; 5, $R_T > 7.3$. All values are in mm. Similar category breaks were found for neighboring ecoregions.

[C] Model results from B. M. Wotton (unpubl. data) from the implementation of the Wotton and Martell (2005) model into operations in the province of Ontario. Similar results were also found for models developed for the province of Saskatchewan using the same model form.

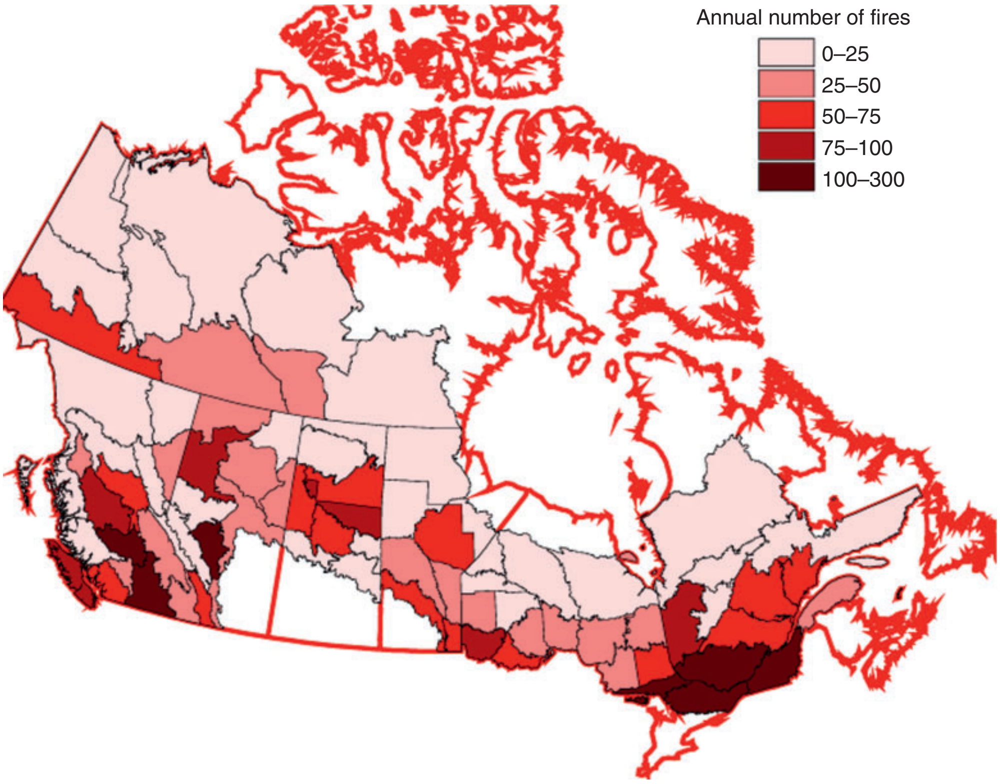

Fig. 2. Annual human-caused fire occurrence rates (number of fires per year) for ecoregions throughout the study area. Numbers in the legend represent mean annual number of fires. The number of years each value is based on varies from province to province (from 16 to 26 years) due to the length of fire records available from provincial fire agencies (Table 1).

We examined how values of FFMC and DMC (two main predictors of human- and lightning-caused fires respectively) changed between the GCM scenarios by calculating changes in the 90th percentile levels of these distributions. Ninetieth percentile values rather than means or medians were chosen because examining the tails of these moisture code distributions tends to be more revealing of true levels of fire potential since the majority fire activity occurs on these drier days (Flannigan and Wotton 2001).

Future fuel moisture scenarios from the GCMs were then used with the models described in the previous two sub-sections to generate future scenarios of fire occurrence. Daily fire occurrence predictions were aggregated to create estimates of annual fire occurrence rates in each ecoregion, as well as each for each province.

DMC, which strongly influences expected lightning fire occurrences, is an open ended index; that is, as the forest floor dries it continues to increase in value with no true maximum. After initial data analysis, we concluded that because of the exponential link function in the Poisson model form, it would be unrealistic to allow values of the DMC to exceed levels observed currently in Canada. Therefore, we calculated a maximum DMC value for each ecoregion from the historical dataset and did not allow DMCs in future GCM-based scenarios values to exceed this value. For the very small number of days[D] where a future DMC value exceeded the observed present day maximum for an ecoregion, its value was set equal to the present day maximum. While the introduction of this DMC cap was a conservative assumption, we believed that it was reasonable given that it reduced the potential for unrealistic predictions from the fire occurrence model. FFMC, the main predictor of the human-caused fire models and an important predictor in the lightning fire models, has an upper limit built into the code and thus did not require a similar limiting function.

Results

Figs 2 and 3 show maps of present day average annual fire occurrence for each of the ecoregions of our study area. The differences in size of each ecoregion makes absolute comparisons of occurrence rates somewhat difficult (particularly as large ecoregions tend towards more northern areas); however, as would be expected, high human-caused fire occurrence rates tend towards the high population density areas of the country (e.g. central and eastern Ontario, south-western Quebec, central southern British Columbia). Overall, mean annual fire occurrence rates in ecoregions vary from a minimum of two

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[D] Historical DMC maximums were only exceeded in the Hadley 2090 general circulation model (GCM) scenario in the provinces of British Columbia, Ontario and Quebec and only on 0.08, 0.6 and 2.3% of ecoregion-days respectively and in the CCC 2090 GCM only in Ontario on 1.8% of ecoregion-days.

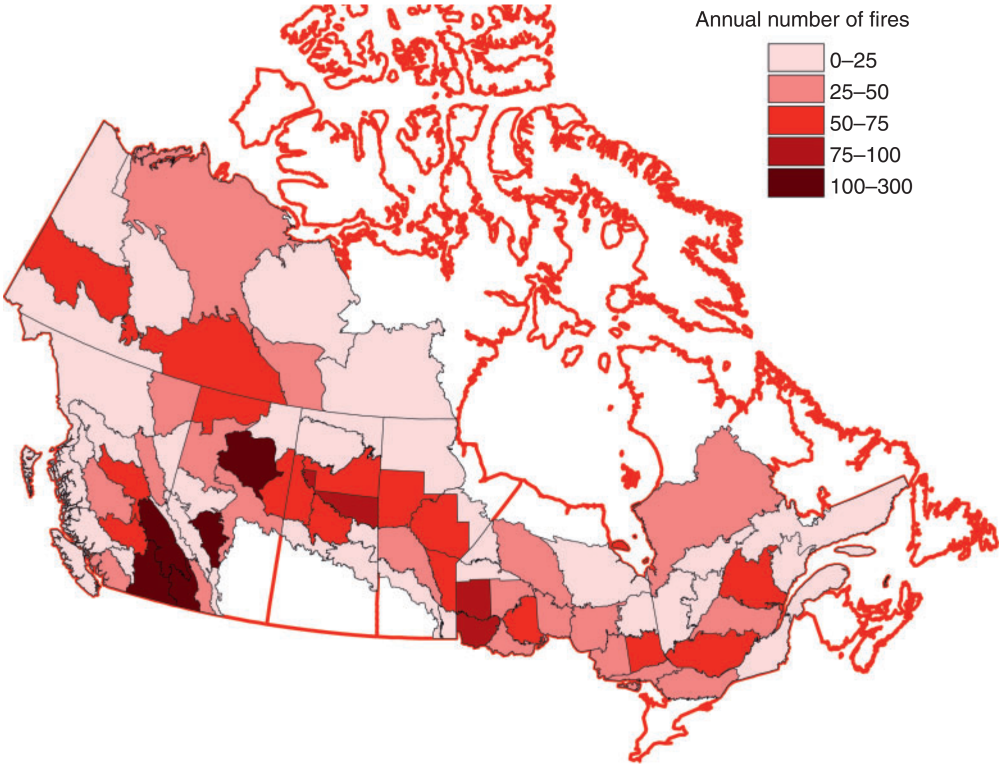

Fig. 3. Annual lightning-caused fire occurrence rates (number of fires per year) for ecoregions throughout the study area. Numbers in the legend represent mean annual number of fires. The number of years each value is based on varies from province to province (from 16 to 26 years) due to the length of fire records available from provincial fire agencies (Table 1).

Table 2. Human-caused fire occurrence rates for each province or territory in Canada using data observed from each fire agencies records and expected fire occurrence generated using fire occurrence models and general circulation model (GCM) datasets

The range in observed years over which this actual estimate has been calculated is listed in Table 1. CCC, Canadian Climate Centre; HAD, Hadley Centre

Province or territory	Average annual human-caused fire occurrence rate (percentage change from baseline GCM scenario)					
	Observed	CCC 1975–1995	HAD 1975–1990	CCC 2020–2040	CCC 2080–2100	HAD 2080–2099
British Columbia	1185	565	606	618 (9)	683 (21)	1145 (89)
Alberta	463	234	196	256 (9)	277 (18)	303 (54)
Saskatchewan	359	208	73	218 (5)	234 (12)	114 (57)
Manitoba	277	335	135	430 (28)	535 (60)	227 (68)
Ontario	821	610	411	734 (20)	928 (52)	837 (104)
Quebec	644	305	269	339 (11)	423 (38)	632 (135)
Yukon	66	23	25	23 (0)	25 (10)	30 (20)
Northwest Territories	107	112	66	145 (29)	137 (22)	61 (−8)
Total	3922	2392	1781	2763 (16)	3242 (26)	3349 (88)

human-caused fires per year in ecoregion 71 of Manitoba to a maximum of 299 lightning-caused fires per year in the northern half of ecoregion 205 (labelled 2051 in Fig. 1) of British Columbia. Overall, annual occurrence rates in the provinces and territories are in Tables 2 and 3.

Development and description of daily fire occurrence models was not the primary purpose of this paper but was a necessary first step to achieving the objective of examining potential changes in forest fire occurrence rates across the country under climate change scenarios. As such, we used established methodologies (following Wotton *et al*. 2003; Wotton and Martell 2005) and examined known fire occurrence predictors to develop the ecoregion-based models of fire occurrence in each province. We have not attempted to explore and document new significant relationships between current environmental factors and fire occurrence in each province, but merely to form sound models of fire occurrence based on the best current understanding of forest fire occurrence and the datasets available. Thus, we will not present

Table 3. Lightning-caused fire occurrence rates for each province or territory in Canada, using data observed from each fire agencies records and expected fire occurrence generated using fire occurrence models and general circulation model (GCM) datasets

The range in observed years over which this actual estimate has been calculated is listed in Table 1. CCC, Canadian Climate Centre; HAD, Hadley Centre

Province or territory	Average annual lightning-caused fire occurrence rate (percentage change from baseline GCM scenario)					
	Observed	CCC 1975–1995	HAD 1975–1990	CCC 2020–2040	CCC 2080–2100	HAD 2080–2099
British Columbia	1259	563	978	612 (9)	679 (21)	3409 (350)
Alberta	533	634	245	712 (12)	815 (29)	522 (110)
Saskatchewan	335	579	80	635 (10)	724 (25)	163 (100)
Manitoba	287	546	124	750 (37)	1096 (100)	257 (110)
Ontario	635	982	393	1596 (62)	3475 (250)	1202 (210)
Quebec	288	201	124	209 (4)	253 (26)	324 (160)
Yukon	86	22	18	24 (10)	30 (40)	24 (34)
Northwest Territories	209	222	77	375 (69)	345 (55)	78 (1)
Total	3632	3749	2039	4913 (31)	7417 (98)	5979 (190)

the results of this modelling in detail. Model forms are presented in Appendices 1 and 2 (available as an Accessory publication, available from the journal online) for those interested in using the models in other climatological studies of fire occurrence. A short description of some of the general model results follows.

Across the provinces, FFMC was indeed a strong predictor of the expected daily number of human-caused fire arrivals in a region. This agrees with the results of numerous studies (Martell *et al.* 1987, 1989; Poulin-Costello 1993; Vega-Garcia *et al.* 1995; Wotton *et al.* 2003, 2005). There were significant differences between ecoregions both in terms of absolute number of fires predicted and through ecoregion interactions with the FFMC: this agrees with the findings of Wotton *et al.* (2003) in Ontario. The human-caused fire subtype grouping also had a strongly significant influence on expected number of fires in all provinces where data existed as did the seasonal breakdown (i.e. spring and summer).

Our lightning-caused fire models across the country confirmed what has been found in other research done in Ontario (Flannigan and Wotton 1991; Wotton and Martell 2005) and Alberta (Krawchuk *et al.* 2006): DMC was a very good indictor of lightning fire ignition. It was statistically significant in each province or territories model. FFMC was also a significant factor influencing the number of lightning-caused fires expected on any particular day, which was also found in previous research from which the model used here were based (Wotton and Martell 2005). FFMC plays an important role in lightning fire occurrence because of its influence on arrival probability; that is, the probability that a fire will be active enough (generating sufficient heat and smoke) to be detected and reported to a fire management agency.

Fig. 4 is a log-log plot of total number of fires predicted by the models for each forested ecoregion across the country for each year of the record compared with observed numbers. We plot in log-log space because for most ecoregions, the predicted and observed numbers of fires are relatively small. Therefore, there is a high degree of clustering at less than 100 fires per year. In addition, the non-transformed predicted *v.* observed plot shows a characteristic increasing of variance with increasing fire numbers, which can be expected from a process that can be modelled with a Poisson distribution. The plots show general agreement between predicted and observed numbers for both human- and lightning-caused fires. Correlation coefficients for the relationship in transformed space were $r^2 = 0.87$ ($n = 1668, P < 0.0001$) and $r^2 = 0.76$ ($n = 1672$, $P < 0.0001$) respectively; correlation coefficients for the untransformed values were similar ($r^2 = 0.88$ and 0.76 respectively). These levels of correlations were similar to those found in a study of lightning caused fires in Ontario ($r^2 = 0.86$) by Wotton and Martell (2005). While the relationships appear reasonable over a wide range of annual fire occurrence, Fig. 4 does appear to indicate a slight over-prediction in the models for low fire years, particularly for the lightning fire models.

Climate change scenarios

Fig. 5 shows summertime (May through August) temperature and precipitation change across the country in the 2030 and 2090 scenario for the CCC GCM as summarized within each ecoregion. The temperature maps (Fig. 5*a*, *b*) show 1 to 2-degree changes from the baseline GCM scenario (1975–1995) for most of the country by 2030 and increases of over 4 degrees by the end of the century. A map temperature change from baseline levels (1975–1990) predicted by the Hadley Centre GCM (Fig. 6*a*) shows a very similar level of warming across the country by the end of the century.

Percentage change in total summertime rainfall based on the Canadian Climate Centre scenarios are in Fig. 5*c*, *d*. This value, expressed as a percentage, represents the difference between total future summertime rainfall (May through August) and total rainfall from the baseline scenario all divided by the mean total summertime rainfall amount from the baseline GCM scenario ($100 \times [\mathrm{RAIN}_{\mathrm{future}} - \mathrm{RAIN}_{\mathrm{current}}]/\mathrm{RAIN}_{\mathrm{current}}$); thus, positive values indicate an increase in rainfall in the future in a region. This ratio is expressed as a percentage change from the baseline value in Fig. 5*c*, *d* and shows a complex pattern of areas with increased rainfall mixed with areas of decrease in the 2030 scenario. By the end of the 21st century, the Canadian Climate Centre's 2090 scenario shows a general increase in rainfall across the country. Examining seasonal rainfall change in the 2090 scenario of the HAD model compared with its baseline scenario shows a general increase in summertime rainfall across the country in the future (Fig. 6*b*) though the pattern of these

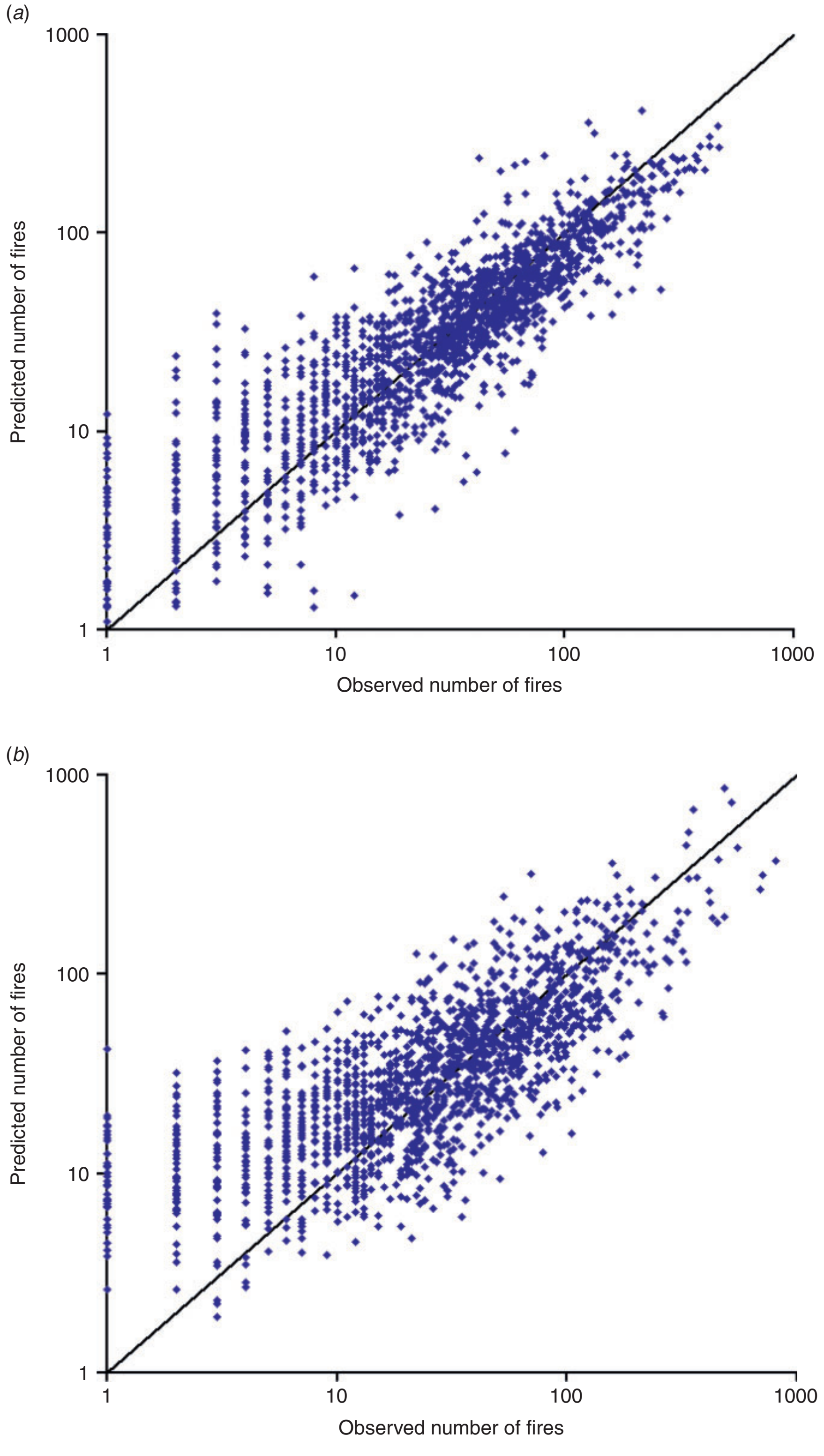

Fig. 4. Predicted number of fires *v.* observed for (*a*) human- ($r^2 = 0.87$, $P < 0.0001$) and (*b*) lightning-caused ($r^2 = 0.76$, $P < 0.0001$) fire occurrence models developed here. Each point represents number of fires per year in an ecoregion.

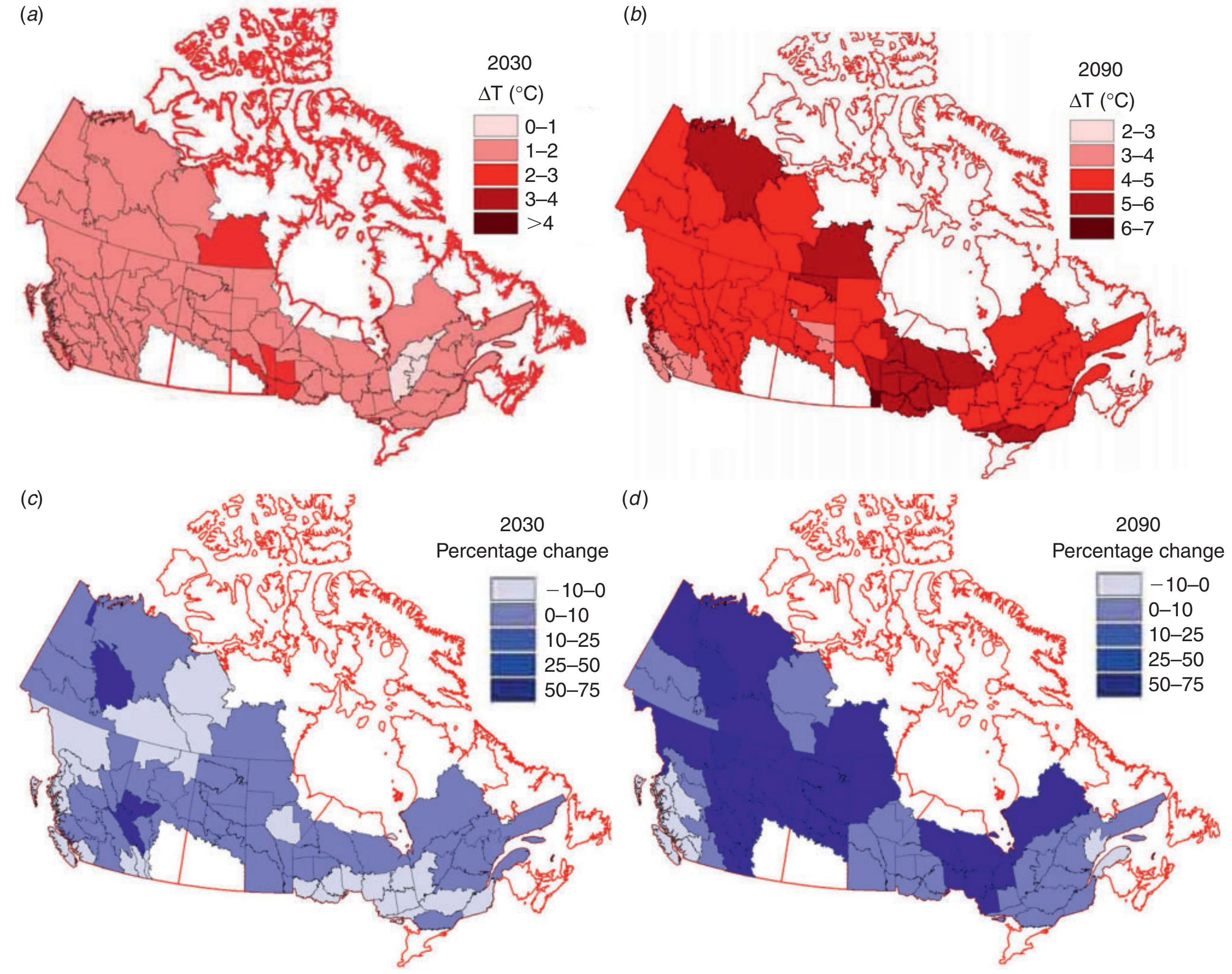

Fig. 5. Maps of changing summer temperature and rainfall projected from the Canadian Climate Centre general circulation model (GCM). Changes in temperature for (*a*) 2030 and (*b*) 2090 represent difference between seasonal average in the future scenario and the baseline scenario in degrees Celsius. Rainfall change maps for (*c*) 2030 and (*d*) 2090 represent the difference between total future summertime rainfall and total rainfall from the baseline scenario all divided by the mean total summertime rainfall amount from the baseline GCM scenario ($100 \times [\mathrm{RAIN}_{\mathrm{future}} - \mathrm{RAIN}_{\mathrm{current}}]/\mathrm{RAIN}_{\mathrm{current}}$).

increases is spatially different that that observed in the CCC model (Fig. 5*c*, *d*).

The change in 90th percentile for the FFMC was quite small. The mean value for all the ecoregions from the baseline GCM scenario was 86 and values increased in the future GCM scenarios as a whole but overall only by ~1.6 points (range was −0.9 to 2.6) by the end of the century in the HAD model and by 0.7 point (range was −0.7 to 2.3) in the CCC model. When converted to actual litter moisture content (using the standard FWI System relationship), these changes correspond to changes in actual fuel moisture content of roughly 1.6 and 0.7% respectively.

Changes in 90th percentile DMC values were more spatially variable than 90th percentile values of FFMC across the country and greater in terms of their absolute level of change. Across the ecoregions studied between the baseline and 2090 scenario from the HAD model, the 90th percentile DMC increased from 28 to 39, while for the corresponding time periods in the CCC model the 90th percentile DMC values increased from 38 to 49. These differences amount to an absolute drying of the forest floor by ~30% gravimetric moisture content. The percentage relative change in 90th percentile DMC level is in Fig. 7 for each of the future scenarios, and reveals the spatial variability in these changes across the country.

Tables 2 and 3 summarize the current and future annual human- and lightning-caused fire occurrence rates for the forested region of each province and territory studied. Table 2 shows that the baseline GCM scenarios tended to under-predict human-caused fire occurrence rates across the country. This is most likely because GCM baseline scenarios tended to be somewhat wetter that than the current climate, lowering fuel moisture levels and leading to lower than expected number of fires. Results from the baseline GCM scenarios and the lightning models (Table 3) showed similar under-prediction from the Hadley Centre model while numbers of fires from the Canadian Climate Centre were similar to those observed. This agreement would suggest DMC levels in the CCC baseline scenario were

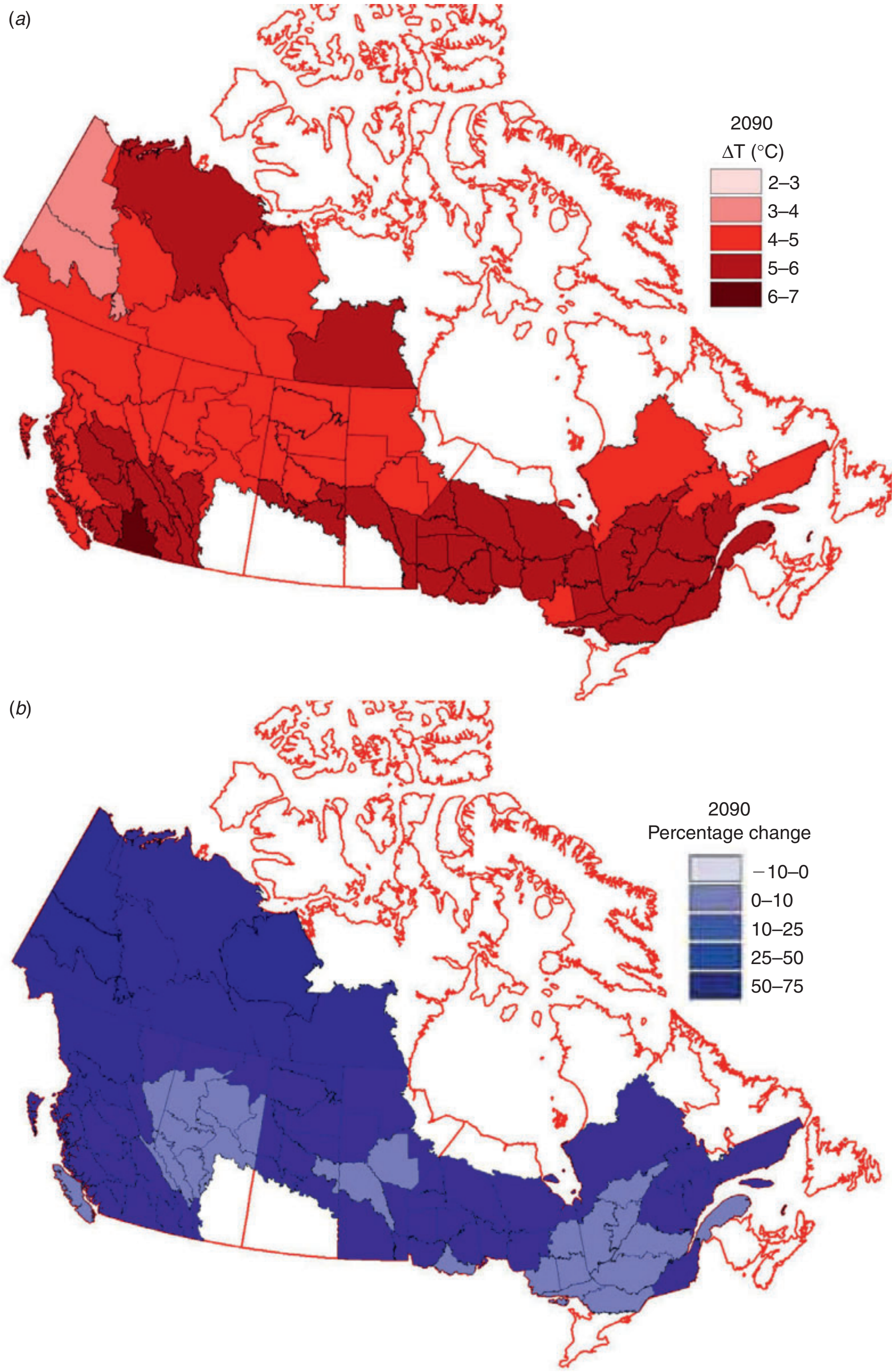

Fig. 6. Maps of changing temperature and rainfall projected from the Hadley Centre general circulation model (GCM) for the 2090 time slice. Changes in (*a*) temperature are in degrees Celsius and represent difference between seasonal average in the future scenario and the baseline scenario. (*b*) The rainfall change map for 2090 represents the difference between total future summertime rainfall and total rainfall from the baseline scenario all divided by the mean total summertime rainfall amount from the baseline GCM scenario ($100 \times [\mathrm{RAIN}_{\mathrm{future}} - \mathrm{RAIN}_{\mathrm{current}}]/\mathrm{RAIN}_{\mathrm{current}}$).

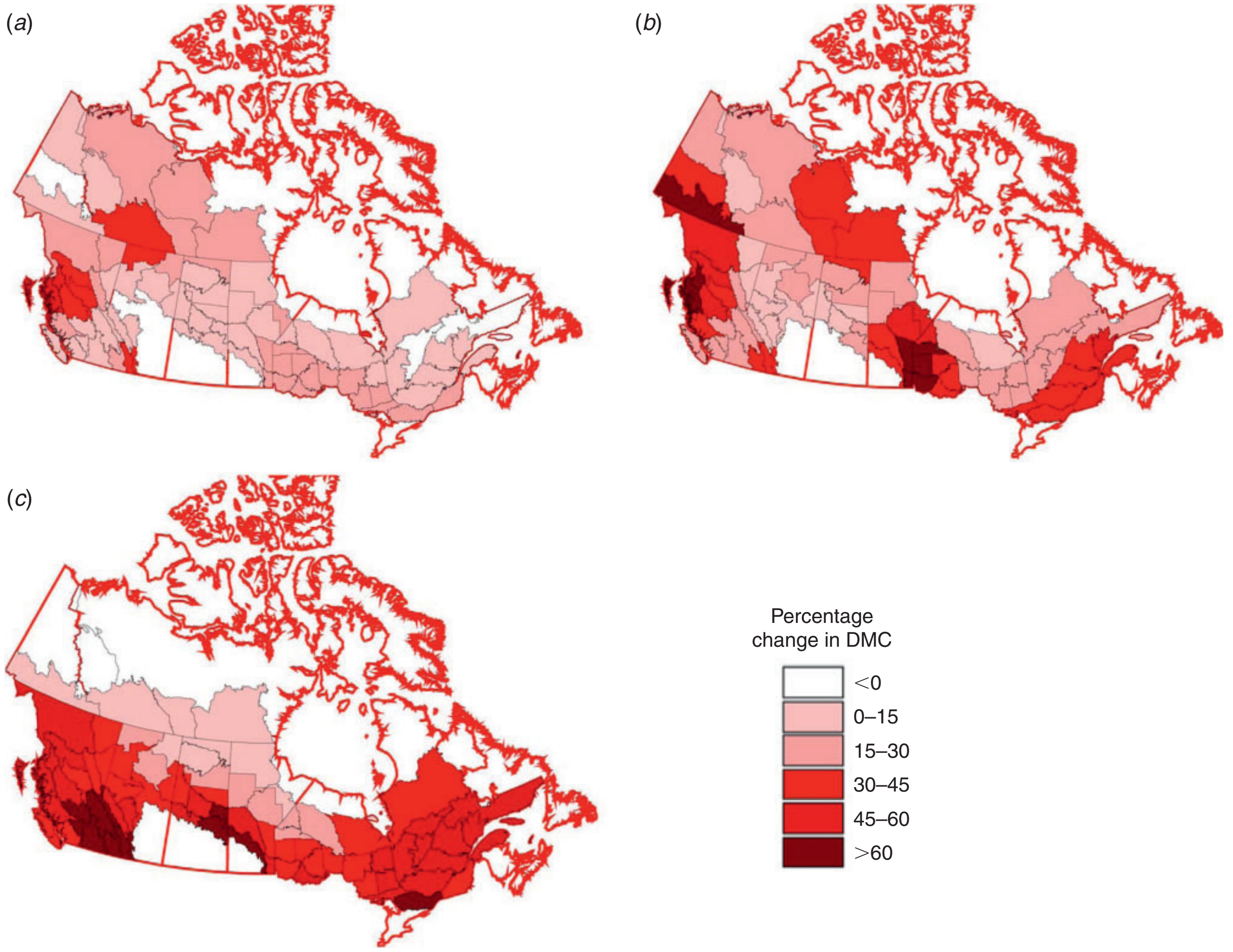

Fig. 7. Percentage change in 90th percentile level of DMC value for (*a*) the CCC 2030 scenario, (*b*) the CCC 2090 scenario and (*c*) the HAD 2090 scenario.

comparable to actual values for this period. This would imply that rainfall differences between the current observed weather and CCC baseline were comprised mainly of more frequent small events, under the 1.5 mm rainfall threshold below which DMC is not influenced by rainfall. Overall the under-prediction seemed strongest in the Hadley Centre model; however, as with previous studies of climate change and fire danger, where wet scenarios reduced absolute danger rating levels (e.g. Flannigan *et al*. 1998, 2000), we considered results from future scenarios always in relation to those initial predictions from the baseline scenarios (percentage change from baseline).

Overall, increase in fire occurrence from the baseline CCC GCM scenario is shown for the 2030 and 2090 time periods for human and lightning fire cause groups in Fig. 8. Fig. 9 shows the equivalent maps for the HAD GCM scenarios. Increases in overall fire occurrence for each of the future scenarios from the Canadian Climate Centre and Hadley Centre GCMs are summarized by each province in Table 4. Overall, the Hadley Centre model shows larger increases in forest fire occurrence across the country, predicting an overall increase in fire activity by the end of the 21st century of just under 150%. The corresponding overall increase in fire occurrence from the Canadian Climate Centre based projections was 74%; the increase for the 2030 time slice was ~25%. In the study by Flannigan *et al*. (2005) using the same GCM scenarios, projected area burned for the country increased by about 75% by the end of the century using the CCC scenario and 150% for the same time period from the HAD scenario. These values agree quite closely with changes in fire occurrence levels found here. Increases in area burned in the Flannigan *et al*. (2005) study were greatest at northern latitudes across the country in the CCC scenario, while Fig. 8 shows increases in both human and lightning fire activity are greatest in central Canada. The results in Flannigan *et al*. (2005) for the Hadley model showed expect increases across the entire country, whereas in terms of fire occurrence, we see strong increases mainly through the southern and central boreal forest sections of the country.

Discussion

Overall output from both GCMs shows increased dryness in fuel moisture leads to increased fire activity across the country. This

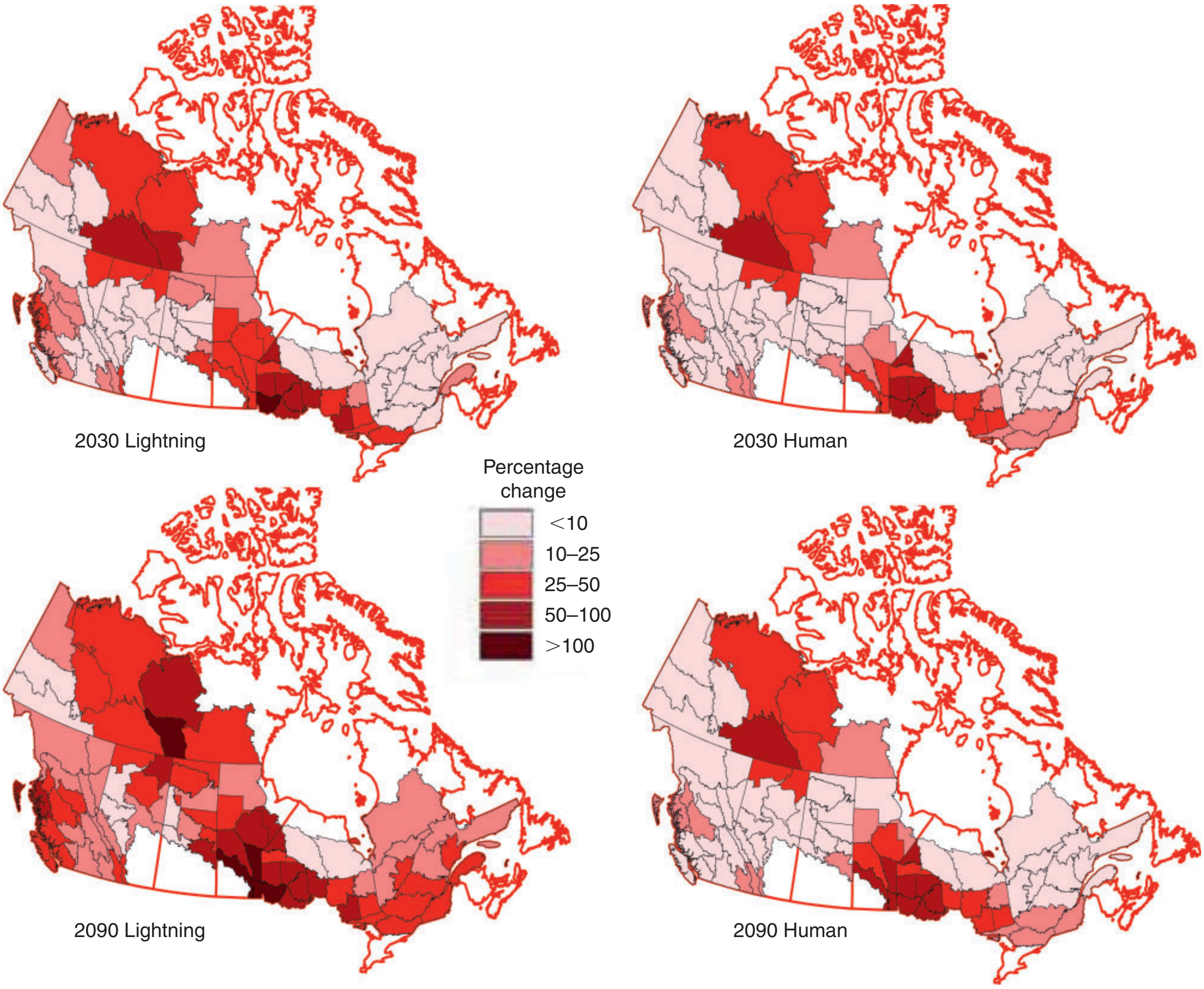

Fig. 8. Relative change (percentage increase) in fire occurrence between future and baseline scenarios for the Canadian Climate Centre general circulation model (GCM). Relative change is given as the percentage increase in number of fires predicted by the GCM (future scenario minus baseline scenario) divided by the total number of fires in the baseline scenario.

increase in fire occurrence projected from the output of the two GCMs is driven most strongly by increases in lightning fire activity. Across the country, the Canadian Climate Centre results show human-caused fire increasing by just 16% in the 2030 period and 36% in the 2090, with corresponding changing in lightning fire occurrence rates at 31 and 98% respectively. The overall increase in fire occurrence from the Hadley Centre model is 88% for human-caused fire and almost 200% for lightning-caused fires. Given the under-prediction in baseline fire occurrence by the fire weather generated from the Hadley Centre model, these results should be interpreted with some degree of caution. Wotton *et al.* (2003) developed human-caused fire occurrence models for ecoregions within the province of Ontario. Their projections of increases in fire occurrence, using both the CCC and HAD model (50 and 77%), agree with increases in projected for Ontario in this current work. In a further study in Ontario, Wotton *et al.* (2005) used a very conservative approach to modelling lightning fire occurrence across the province and projected an 80% increase in lightning fires by the end of the 21st century: projected values for Ontario from this study (Table 3) are three times this increase. Krawchuk *et al.* (2009) used RCM output (from the Canadian RCM, which is initialized with output from the CCC GCM: Laprise *et al.* 2003) to estimate potential change in lightning fire occurrence in a study area in north-eastern Alberta. They projected an increase in lightning fire occurrence of 80%. The average increase in lightning fire occurrence for Alberta in this study is 30% (CCC model) and 110% (HAD model), though the ecoregion specific maps reveal that in the area of the Krawchuk *et al.* (2009) study the agreement between results of that study and this current work are probably closer.

Examining potential regional changes, the Canadian Climate Centre model and Hadley Centre model both show strong increases in lightning fire activity through Ontario and into southern Manitoba. Strong increases in lightning fire activity in Canada's Northwest Territories (NWT) appear only in the results of the Canadian Climate Centre model, reflecting the significant

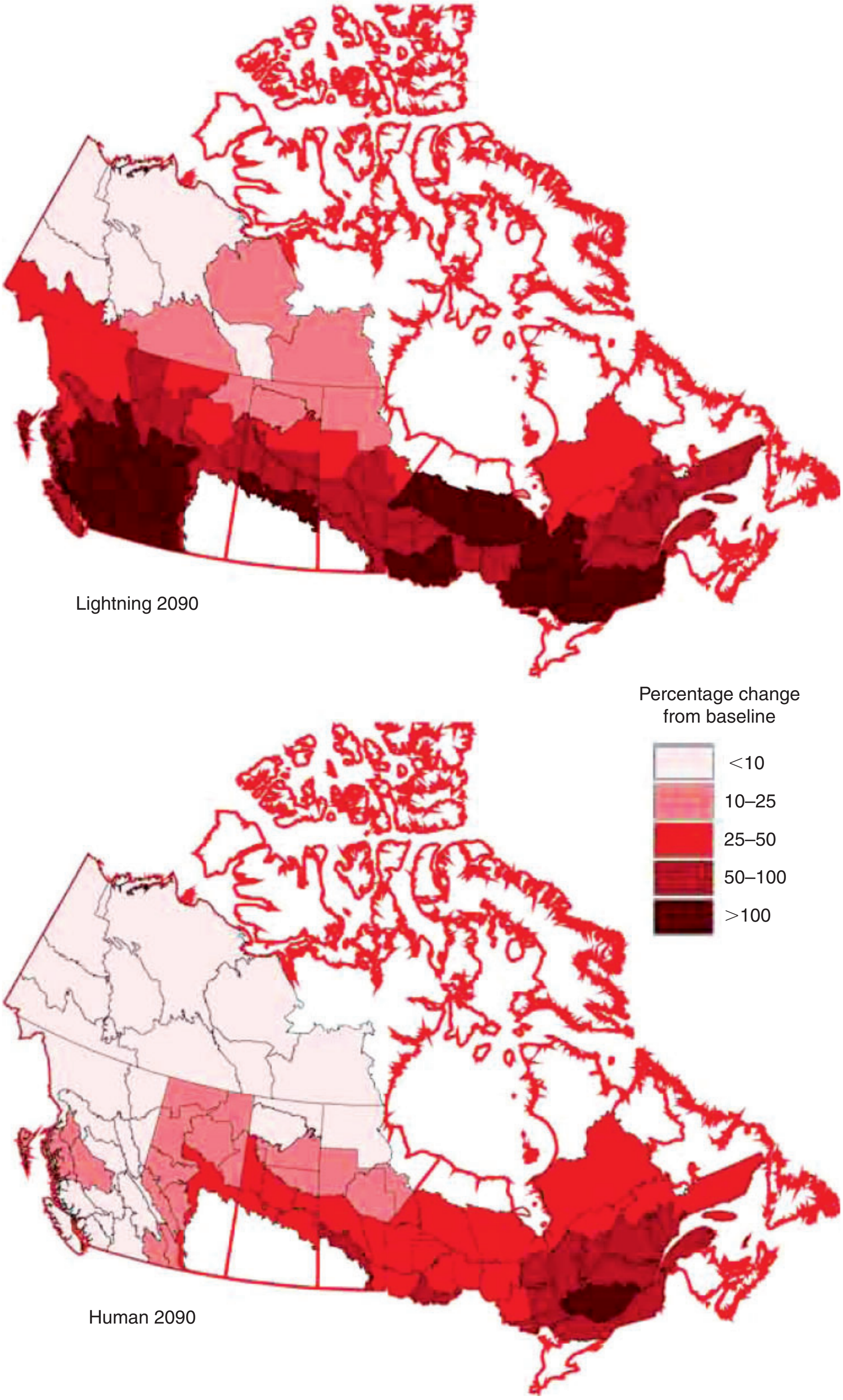

Fig. 9. Relative change (percentage increase) in fire occurrence between future and baseline scenarios using the Hadley Centre general circulation model (GCM). Relative change is given as the percentage increase in number of fires as predicted solely by the GCM; that is, future scenario (2080 to 2099) minus baseline scenario (1975 to 1990) divided by the total number of fires in the baseline scenario (1975–1990).

Table 4. Projected total change (percentage above current levels) in forest fire occurrence expected in each province or territory using the projections of the Canadian Climate Centre and Hadley Centre models

Province or territory	Projected increase (%) in total annual fire occurrence rate		
	Canadian Climate Centre		Hadley Centre
	2020–2040	2080–2100	2080–2099
British Columbia	9	21	190
Alberta	11	26	87
Saskatchewan	8	22	82
Manitoba	34	85	87
Ontario	46	180	150
Quebec	8	33	140
Yukon	5	24	26
Northwest Territories	46	43	30
Total	25	74	144

increase in rainfall the Hadley model generates in the north of Canada. This increase in lightning fire activity shown by the Canadian Climate Centre model agrees with other studies of changing fire danger, which show the near-arctic in Canada as being an area particularly vulnerable to climate change, and a likely location to see initial effects of the changing climate (Soja *et al.* 2006).

There are clearly some significant differences in the projections of the Canadian Climate Centre and the Hadley Centre GCMs at the regional level that have contributed to the overall difference in the projections of fire occurrence. Fig. 6*b* shows that the regional pattern of rainfall increase across Canada projected by the HAD model differs from that projected by the CCC model (Fig. 5*d*). It would reasonable to assume that these differences in rainfall contribute to a large part of the differences in the patterns of overall fire occurrence change between the two CMs, given the relative consistency of the spatial patterns in future temperature (Figs 5*b*, 6*a*). Model intercomparisons of major GCMs (including both the Hadley and Canadian Climate Centre models) used as part of IPCC assessment reports (Meehl *et al.* 2007; Randall *et al.* 2007) have shown that the models typically agree on temperature at large time and space scales but there is less consensus on precipitation. This divergence between GCM outputs is common in GCM intercomparisons and would be most evident when comparing regional differences. A GCM scenario of future climate is just a plausible representation of future climate given the assumptions and parameterizations within the physical system being modelled. In this regard, it is useful to think of the two GCM outputs as providing two possible representations of future conditions, both wetter than current for the most part but with different spatial distributions for that moisture.

The Hadley model tends to predict larger increases in lightning fire activity through the southern parts of the Prairie Provinces (Alberta, Saskatchewan and Manitoba) and Quebec than are seen in the corresponding scenarios from the Canadian Climate Centre. The difference between the Hadley Centre and Canadian Climate Centre predictions is most extreme in the province of British Columbia; however, GCM outputs for this area (and the subsequent fire occurrence projections) must be interpreted with considerable caution as the large grid cell structure used in the GCMs does not resolve the true elevation of the mountains. Thus, GCM projections represent fire weather at average elevations across a large cell (~400 × 400 km), whereas fire weather station outputs typically characterize the fire weather in forested valley bottom areas. Flannigan *et al.* (2005) found the same strong differences (between these two GCMs) in their future projections of area burned for British Columbia and parts of Alberta.

Caveats

It is particularly important in climate change impacts studies to review assumptions and uncontrolled sources of variability that may have some influence on projections made. The projections presented here are based on two well established and internationally used GCM models. Differences in fire climate projected by these two models lead to different projected levels of increase in fire activity in some regions. It is likely that differences in rainfall patterns drive a great deal of the regional differences between the two models. However, a detailed investigation of these patterns was beyond the scope of this study. The future fire occurrence scenarios derived from these two GCMs should be regarded as two possible realizations of possible fire occurrence in a future with climate change: it is important to remember that they do not represent specific predictions of the future.

Neither of our fire occurrence models accounts for detailed forest type information. The use of ecoregion and the inclusion of ecoregion interactions with the key moisture content variables can account for coarse scale vegetation differences; however, forest type change (which one can readily assume would accompany climate change) are not accounted for in these model projections. For the boreal forests of Canada, this lack of change in forest composition seems reasonable for projections of activity over the next several decades, as only a small fraction of the forest is disturbed each year; however, examining the impact of forest change should be considered a crucial aspect of future studies of long-term impacts of climate change on Canadian forest fire regimes.

The lightning-caused fire occurrence models presented here were developed without using lightning as a predictor or in the estimation of expected number of ignitions (as in Wotton and

Martell 2005). This leads to an increased level of variability in the predictions from these models (compared with, for example, the fire management operations focussed models of Wotton and Martell 2005). Thus, these projections do not explicitly account for changes in lightning activity that is projected to increase under climate change (Price and Rind 1994; Arif 2006). However, rainfall intensity was used as a surrogate for lightning presence and thus, an increase in rainfall rate may act in this model to indicate an increase in lightning activity accompanying climate change. We have also capped DMC values in future projections with historical ecoregion maximums to avoid unrealistically large projections due to the open-ended nature of the DMC. This would tend to make projections slightly conservative, though for the most part across the country, DMC values were not unrealistically high in future scenarios. Furthermore, we weigh this potential introduction of conservative estimates against the danger of extrapolating beyond the environmental conditions under which models were developed and feel this assumption was reasonable.

In terms of human-caused fires, rates of occurrence and their spatial distribution can be influenced by demographics, land use, etc. (e.g. Vega-Garcia *et al.* 1995). We have chosen to use only the most recent 20–25 years of fire data available to limit major changes in patterns of human activity in the forested areas studied. The basic implicit assumption in our models is that the basic social factors governing the presence of human ignition sources on the landscape do not change with time. As with the assumption of static forest type, in the short-term (decades) this assumption seems reasonable, however in the long-term, it is reasonable to expect significant changes in the social elements influencing human-caused fire ignition patterns.

The grid cell resolution of the GCMs is quite large, in the order of 400 km per grid cell side; thus, the mountains on the western coast of Canada are not well resolved. Projections for the province of British Columbia and the Yukon should be interpreted with extreme caution. In such regions where fine scale weather patterns are strongly influenced by local topography, detailed regional impacts studies (e.g. Nitschke and Innes 2008) are needed, and the use of output finer scale models, such as the Canadian Regional Climate Model (Laprise *et al.* 2003) should be considered.

Summary

We used two GCMs to develop projections of future fire occurrence levels across Canada. While fire activity is projected to increase across all forested regions studied, the relative increase in number of fires varies regionally. Overall across Canada, our results from the Canadian Climate Centre GCM scenarios suggest an increase in overall fire occurrence of 25% by 2030 and 75% by the end of the century. Results projected from fire climate scenarios derived from the Hadley Centre GCM suggest fire occurrence will increase by 150% by the end of the century. These general increases in fire occurrence across Canada agreed with national predictions of increases in area burned under climate change (Flannigan *et al.* 2005).

Fires are a significant and natural element of the boreal forests of Canada. Understanding the impact of climate change on forest fire activity is important for understanding long-term change in forests, as well as the size of, and potential emissions from, terrestrial carbon stocks (Flannigan *et al.* 2008). Studies examining all aspects of potential change to the fire regime are important to develop a full understanding of what the forest landscape may look like in the future, both with and without human management of landscapes. The numbers of fires occurring in a region not only influences potential area burned on the landscape but is extremely important to forest fire management as it defines the load on suppression resources a fire management agency will face. Throughout the managed forests of Canada, fires are suppressed and in most of cases, kept to a very small size; it is those fires that escape initial attack that lead to area burned with fires >200 ha in Canada making up only 3% of fires but accounting for over 97% of the area burned (Stocks *et al.* 2002). The greater the fire load in an intensively protected fire management zone, the greater the need for resources. When resource capacities are exceeded, fires can escape and grow large and it is important to understand these fires, as they are critical to understanding to total number of large fires on a managed landscape, and hence total area burned. Thus, it is important to continue this work with an exploration of potential future rates of escape fire occurrence. Studies of initial attack system failure in the province of Ontario (Wotton *et al.* 2005) have shown that under climate change, increased fire occurrence rates lead to even greater increases in escape fire rates. Such findings will be critical for forest fire management agencies trying to plan fire management strategy under climate change.

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