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THE WEATHER OF LARGE FIRES IN THE CANADIAN BOREAL FOREST

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1. INTRODUCTION

Canadian forest fire management agencies use the Canadian Fire Weather Index (FWI) system (Van Wagner, 1987) to estimate fuel moisture and generate a series of relative fire behaviour indices based on weather observations. The current day's indices and future values generated from forecasted weather aid in deploying suppression resources to areas of potentially high fire activity. FWI system indices are relative indicators of potential fire behaviour, however and do not, by themselves, predict differences in expected behaviour between substantially different forest types. While over the years operational personnel have developed experience in understanding the fuel-type specific fire behaviour expected under given values of the FWI system indices, the Canadian Fire Behaviour Prediction (FBP) system (Forestry Canada 1992) is often used to predict fire behaviour (fuel consumption, rate of spread and head fire intensity (HFI)) for a range of fuel types found in the Canadian forest.

HFI estimates the amount of energy released per unit time per unit fire front line (Byram 1959). It is a good indicator of fire behaviour and HFI forecasts are used to assess potential risks to wildland firefighters (Beck *et al.* 2002). Climatologies of HFI have been developed to estimate fire behaviour potential on the landscape, often using 90 or 95 percentile values (Kafka *et al.* 2000). These are based on historical weather and give the potential for a fire to occur at a given intensity.

This paper reports the FWI system indices and HFI values experienced as extreme events based on daily weather for fires with a final size of greater than 2 km^2 in area in the boreal and taiga ecozones of Canada (Fig. 1). We use data from the large-fire database (Stocks *et al.* 2003) for the 1959 to 1999 period. These large fires represent only a small percentage of the fires but account for most of the area burned. We also test whether there have been trends in the indices over the 41-year period.

2. METHODS

The FWI components were calculated using noon-hour (local standard time) values of temperature, relative humidity and wind speed, and 24-h total precipitation. The data were taken from Environment Canada surface observation stations that operated for a full fire season for at least part of the analysis period. We used noon observations from 415 hourly weather stations distributed across the country. Weather data from the Ontario Ministry of Natural Resources fire weather station archive from 1963 to 1997 were also included to improve the weather station network coverage in northern Ontario. Rainfall data from 90 stations in Environment Canada's daily climatological network were also used to augment the noon records in areas of the country prone to fire but with very sparse hourly weather station coverage. These weather and fire danger data were interpolated to each fire location within the LFDB for the start date and the following 20 days using a thin-plate cubic-spline technique (Flannigan and Wotton 1989).

For each fire, we identified the highest daily reported value of a FWI system index within the 21-day period. This gives the most severe fire weather condition for each fire, representing an extreme. Extremes are appropriate since they dictate fire growth but they do not represent typical conditions experienced over the whole period during which the fire burns. We then used these values to derive statistics for each ecozone and for each year. The fire weather parameters (Van Wagner 1987) were:

FFMC (Fine Fuel Moisture Code) represents the moisture content of litter and other fine fuels in a forest stand, in a layer of dry weight about 0.25 kg/m^2 (time constant about 2/3 days). It is an indicator of sustained flaming ignition and fire spread.
DMC (Duff Moisture Code) represents the moisture content of loosely compacted, decomposing organic matter weighing about 5 kg/m^2 when dry (time constant about 12 days). It relates to the probability of lightning ignition and fuel consumption.
DC (Drought Code) represents a deep layer of compact organic matter weighing about 25 kg/m^2 when dry (time constant about 52 days). It relates to the consumption of heavier fuels and the effort required to extinguish a fire.

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ISI (Initial Spread Index) is a combination of wind and FFMC representing rate of spread without the variable influence of fuel.
BUI (Build-up Index) is a combination of DMC and DC representing total fuel available to the spreading fire. It is correlated with fuel consumption.
FWI (Fire Weather Index) is a combination of ISI and BUI representing intensity of the spreading fire as energy rate per unit length of fire front. It is often used as a single integration of fire weather.
DSR (Daily Severity Rating) is a power function of FWI representing a measure of control difficulty for a fire.

All of these are unit less. In addition, we calculated the HFI as the amount of energy released per unit time per unit fire front line, based on fuel consumption and fire rate of spread as part of the FBP System. Unlike the previous FWI parameters, HFI is dependent on the fuel type, and has units of MW m^{-1}. It is a function of fuel consumption and rate of spread, assuming the heat of combustion is a constant 18 MJ kg^{-1}. The FBP system includes several fuel types that occur throughout the boreal forest. For this analysis, we based the HFI calculations on the boreal spruce (C2) fuel type only. This fuel type occurs throughout the boreal and taiga regions and is used for comparison purposes, but it does exhibit extreme fire behaviour. Analyses for additional fuel types would give different HFI values.

3. RESULTS AND DISCUSSION

FFMC values range between 85 and 97 with means for an ecozone in the range of 90 to 92 (the FFMC is a non-linear scale). The highest values are found in the Boreal Plains and Boreal Cordillera ecozones and the lowest in the Taiga Shield ecozones (Table 1). All ecozones have significantly different values, except that the Taiga Plains and Boreal Shield East are similar. DMC values range from about 10 to 140 with the median values between 30 and 70. The Taiga Plains and Boreal Plains have similar DMC values, whereas the other ecozones are significantly different. DC values range from about 50 to 700 with lower values in the east. No significant difference in mean DC values was found between the Taiga Plains and Boreal Cordillera, the Boreal Cordillera and Taiga Shield West, and the Boreal Shield East and Taiga Shield East. FWI values are typically between 5 and 50 with median values between about 20 and 30. The Boreal Plains and Boreal Cordillera are not significantly different. Again, the eastern ecozones show lower values.

The ISI values are lowest in the taiga ecozones whereas the BUI values are lowest in the east. These correspond to similar patterns in the other indices, upon which they are based. Similarly the DSR is lowest in the east, and highest in the western boreal ecozones.

Regression analyses of the fire weather indices did not show consistent trends over time with very weak predictability. This is mostly because of large variation among years, even after averaging conditions over the fires.

A climatology of these indices has not been reported for Canada for conditions during which fires were burning. Our distributions of FFMC, DMC and DC differ from the climatological distributions published by Simard and Valenzuela (1972), because they looked at all fire weather data. Their climatological data are more right-skewed for FFMC, and left skewed for both DMC and DC. Harrington *et al.* (1983) looked at a fire weather climatology including monthly extremes, irrespective of whether a fire was burning. Their monthly extremes for FFMC, DMC, DC, BUI and FWI are similar to ours but their extreme ISI values are much higher, probably caused by their selection of periods with very high winds. Hence our distributions and statistics really reflect conditions during which large fires occur.

In general, FFMC and DMC values are slightly greater in the southern and western ecozones, and DC values are greater in the three northern ecozones west of Hudson Bay. These differences are caused by climate, but likely also reflect fire management policies. Many northerly regions have a modified suppression policy, which does not call for all fires to be actively suppressed unless they threaten some value, such as a community. This means that fires with lower FFMC and DMC values may be suppressed effectively in the more southern regions, and may not reach a size of 2 km^2 (i.e., only the extreme conditions allow for escaped fires). FWI and DSR values are lowest in the two eastern ecozones. All indices are significantly different between the Boreal Shield West and East ecozones, supporting the split of the boreal ecozone into two regions. Similarly, there are differences in most indices between the Taiga Shield East and West ecozones.

Maximum HFI values were typically about 10 to 30 MW m^{-1} for the boreal spruce fuel type. About 10% of the fires exceeded 30 MW m^{-1}. However, higher HFI values are more common in the western boreal ecoregions. It is important to note that continuous crown fire occurs at HFI values above about 10 MW m^{-1}. This happens in about 90% of the fires in the south and west ecozones, and about 60% of the fires in the north and east. Values between 13 and 93 MW m^{-1} have been observed during experimental crown fires where more exact measurements have been made (B.J. Stocks *et al*., International Crown Fire Modelling Experiment), so we believe that our estimates are in a reasonable range of observed fire behaviour. We could not detect trends in HFI over time using linear regression, except for the Taiga Shield ecozone. It is important to recognise that our HFI values are for a constant fuel type and reflect changes in fire weather only. Fuel is very important in determining HFI, and fuel changes have also occurred on the landscape over time. Therefore, there could be trends in HFI caused by fuel that we would not pick up in our analysis.

The fire weather index values reported here provide basic information on conditions during which large fires burn in the Canadian boreal forest, and forms a companion dataset to the large-fire data base. Although both the number of fires and area burned have increased over the past 40 years, we cannot detect consistent trends in weather indices associated with these large fires. However, we do expect that a changing climate will make fire weather conditions more severe, resulting in an increase in area burned in the future (Flannigan et al. 2002).

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Figure 1: Map of Canadian Ecozones

Table 1: Parameters for fires > 2 km^2 in area for 1959 – 1999. Weather indices are the maximum value for the first 21 days of each fire, with mean values for fires compiled for each ecozone. HFI values are based on a boreal spruce fuel type. Similar superscript letters denote no significance difference for a parameter among ecozones at the 0.05 level (ANOVA, SYSTAT1997).

Parameter	Ecozone							
	All Canada	Taiga Plains	Boreal Plains	Boreal Cordillera	Boreal Shield West	Boreal Shield East	Taiga Shield West	Taiga Shield East
Number of fires	9333	1209	1635	755	2998	1057	1209	470
FFMC	91.4	91.2^{a}	92.2	92.2	91.5	91.0^{a}	90.6	90.4
DMC	60	72^{a}	70^{a}	78	55	44	60	38
DC	298	372^{a}	266	$366^{a,b}$	288	210^{c}	354^{b}	227^{c}
ISI	13	10^{a}	16	12^{b}	14	12^{b}	10^{a}	10^{a}
BUI	75	92	80^{a}	96	70	54^{b}	80^{a}	50^{b}
FWI	28	27	33^{a}	32^{a}	28	22	25	20
DSR	10	10^{b}	14^{a}	14^{a}	10^{b}	7^{c}	9	7^{c}
HFI, MW m^{-1}	15	18	24^{a}	28^{a}	20	14	16	10