# DEVELOPMENT OF DAILY WEATHER AND FIRE DANGER SCENARIOS USING TWO GENERAL CIRCULATION MODELS

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## ABSTRACT

Fires play an important role in Canadian forests and are largely influenced by the weather. Any changes in future climate may lead to dramatic changes in future fire activity. We examined what changes in climate might occur due to increased levels of greenhouse gases in the atmosphere and the impact that such climatic changes will have on future fire danger. Daily data were obtained from General Circulation Models (GCMs) from the Canadian Climate Centre (CCC) and Hadley Centre for Canada and used to create future scenarios of forest fire danger across the country. We compared the results for each model and time period to look at potential changes in future fire danger and also differences among the various models. The Hadley model suggested increases in seasonal fire severity of 100% to 200% over much of Canada with some areas of even larger increases. Few areas showed a decrease. The CCC model did not show such a clear pattern of increase and generated a different scenario than the Hadley model for much of central Canada. Both models predicted a longer fire season in Canada of a few days in the south up to approximately a month at northerly latitudes. On average the increase was approximately 2 to 3 weeks across Canada. Increased fire activity will be of interest to anyone studying forest biodiversity, productivity, carbon flux, and fire management practices.

*keywords:* Canada, carbon dioxide, climate change, forest fires, General Circulation Models.

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## INTRODUCTION

Fire, an important disturbance that affects Canadian forests, is highly dependent on weather and climate (Johnson 1992, Swetnam 1993, Flannigan and Wotton 2001). This connection between fire and weather means that any change in future climate could lead to an altered fire regime, thus affecting many characteristics of ecosystems. The weather variables that most strongly influence fuel moisture and forest fire danger are temperature, wind speed, relative humidity, and precipitation. In this study, we used the noon values of these variables within the Canadian Fire Weather Index (FWI) System (Van Wagner 1987) to determine potential fire danger for the current climate and under climate change. In particular, the seasonal severity rating (SSR) (Van Wagner 1970) was examined. The SSR is a component of the FWI System that provides a summary of potential fire control difficulty over an entire fire season. In order to consider future climate, modeled weather variables from two General Circulation Models (GCMs) (Canadian Climate Centre [CCC] and Hadley Centre [Had]) were used as input into the FWI System. Past analysis of GCM data for future fire danger scenario development has involved various techniques. Stocks et al. (1998) superimposed

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monthly temperature and precipitation anomalies from four GCMs onto daily weather data from Russia and Canada to get an estimate of fire activity under a 2×$CO_2$ climate (i.e., a doubling of the amount of atmospheric $CO_2$ over current levels in approximately 2050). Flannigan et al. (2000) conducted similar research using monthly anomalies from Canadian and Hadley models for the 2×$CO_2$ scenario. Both studies found fire danger increasing along with longer fire seasons. Since the observed data were used as a baseline, the precipitation frequency did not change with the climate. That representation was unrealistic given that fire severity can be strongly influenced by the frequency of precipitation and Flannigan et al. (1998, 2001) developed future fire severity scenarios using raw daily data from the CCC GCM. Rainfall estimates in those scenarios were high and led to lower than realistic levels of fire danger across all current and future scenarios. The current study used daily data with calibrations performed on the raw data in order to produce 1×$CO_2$ measurements that were similar to current observations. The daily data were an improvement on the anomaly method in that they allowed the precipitation frequency to change, although other adjustments were necessary as described below. The decision to use the daily method was based on the ability to alter the precipitation frequency, which is a critical element in fire activity (Flannigan and Harrington 1988, Flannigan and Wotton 2001).

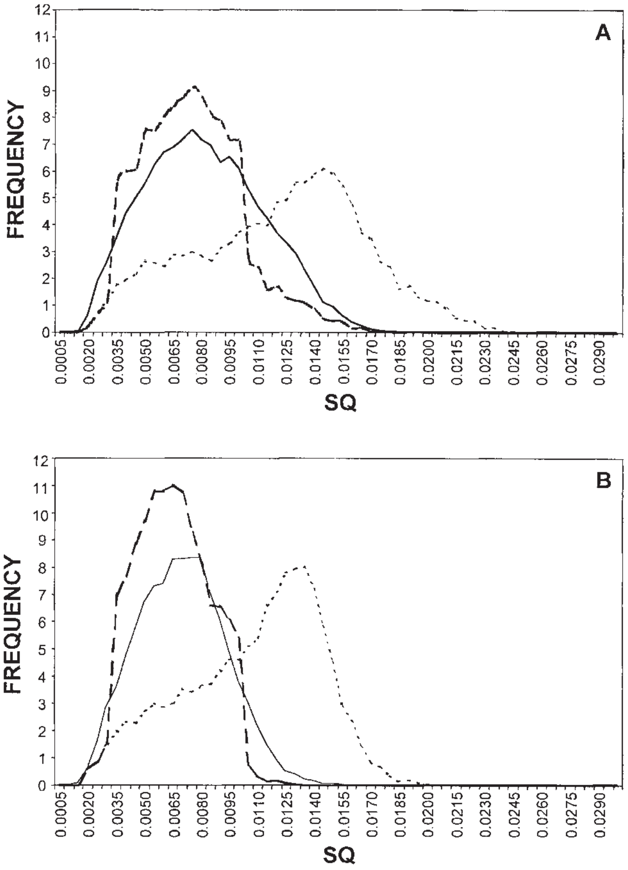

Figure 1. Comparison of specific humidity (SQ) frequencies for AES weather stations and the Canadian Climate Centre's (CCC) General Circulation Model (GCM) for an area in eastern Canada represented by 4 grid cells between 44.54°N to 51.96°N and 84.38°W to 76.87°W (A) and for an area in western Canada represented by 4 grid cells between 51.96°N to 59.27°N and 110.62°W to 103.12°W (B). The solid line represents the AES weather data. The dotted line represents the uncorrected SQ frequencies from the CCC GCM. The broken line represents the SQ frequencies from the CCC GCM after the correction was applied.

## METHODS

### Data

Daily data were collected from both the CCC and Hadley models for two time periods. For the CCC model, 1975–1995 was considered to correspond to a 1×$CO_2$ scenario (representative of current climate conditions), and 1975–1990 was the 1×$CO_2$ scenario for the Hadley model. The CCC model used was the First Generation Coupled GCM (CGCM1). This model included both greenhouse gas and sulfate aerosol forcing contributing to a 1% increase in $CO_2$ per year. At this rate, the time period 2080–2100 roughly corresponded to an approximate tripling in the amount of atmospheric $CO_2$ over current levels and was considered a 3×$CO_2$ scenario. The grid spacing is approximately 3.75° longitude × 3.75° latitude. The Hadley model, HadCM3GGa1, contained only greenhouse gas forcing and output 2080–2099 as its 3×$CO_2$ scenario. The grid for the Hadley model had slightly finer resolution at 3.75° longitude × 2.5° latitude. The variables examined from both models were maximum temperature, 24-hour precipitation, wind speed, and humidity. Noon values were necessary in the analysis. All analysis, with the exception of fire season length, was performed for a fire season of 1 May to 31 August. Fire season length was examined using data between 1 April and 30 September.

### Model Calibrations

While studying the amount of daily precipitation and relative humidity in the models, we noticed that the GCM grid cells appeared to contain more moisture than what was observed by point measurements at the weather stations. This effect has been noted in other studies (Mearns et al. 1995, Skelly and Henderson-Sellers 1996, Osborn and Hulme 1997) while looking

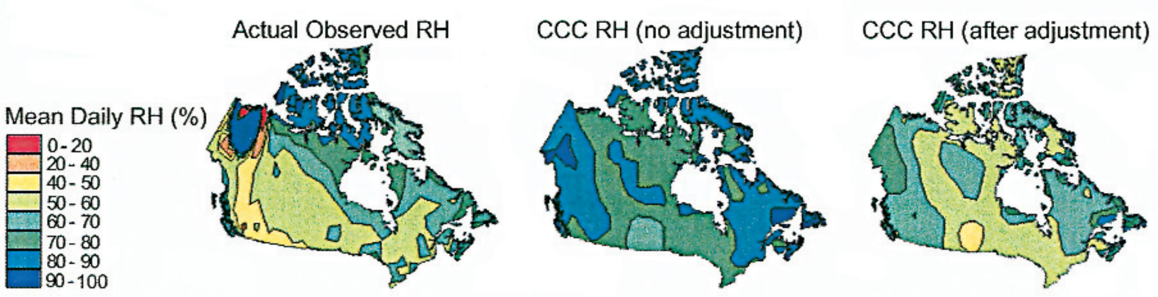

Figure 2. Relative humidity (RH) values from weather station data and from the Canadian Climate Centre's (CCC) General Circulation Model (GCM). Without any adjustment, the CCC GCM predicted a higher RH than was observed. To compensate for this, a new RH was calculated based on a ratio of observed to modeled RH that was a better match spatially to the observed values.

at rainfall event frequencies, and various calibrations have been proposed. We calculated daily rainfall amount frequencies for representative areas in eastern and western portions of Canada and compared them with actual observed frequencies from weather stations. The frequency of duration of rain-free periods was also examined. We attempted to reduce the unrealistic incidence of small frequent daily precipitation by calibrating the modeled precipitation with a daily correction factor (Mearns et al. 1995) for the current time period of each model. The correction factor took the form of a constant amount subtracted off the daily precipitation value. Frequencies were recalculated and compared with the actuals again. These comparisons were repeated using several different correction factors from 0 to 2.5 mm daily until the modeled frequencies were as close to observed as possible. For the CCC model a correction of 2.0 mm per day worked best. For the Hadley model a correction of 1.5 mm per day was most appropriate. These corrections were applied to daily precipitation outputs from both current and future time periods.

The calibrations to humidity in the models involved a different process. Each model had to be treated differently because different variables were output by each GCM. Specifically, the CCC model output specific humidity (SQ). A comparison between the modeled daily specific humidity and observed values indicated that overall the modeled values were higher than actual (Figure 1A,B). A ratio was then calculated for each grid cell of observed to modeled SQ over the 1975–1995 period during the fire season. This ratio was then applied to both the 1975–1995 and the 2080–2100 periods. Comparisons of the SQ frequencies after the adjustment and the observed SQ frequencies (Figure 1A,B) show a closer agreement than before the adjustment. The adjusted SQ was then converted to relative humidity, necessary for input into the FWI System, using the saturation mixing ratio (Baumgartner et al. 1982). Spatially, the adjusted RH is also a better match to the actual observed patterns (Figure 2).

For the Hadley model, RH was a direct output variable so there was no need to look at specific humidity. Instead, a new RH was calculated as a percentage of the saturation vapor pressure to noon vapor pressure, assuming that saturation of the atmosphere occurs at the minimum temperature. The calculated RH was compared spatially with the observed RH for 1975–1990 and was found to be in better agreement than the original modeled RH. This same method was used to correct the RH for 2080–2099.

Wind within the Hadley model was output on a different grid than the other variables because of its vector nature. To be consistent, we interpolated the GCM's estimate of wind speed to the same grid as the other variables and performed all analysis on the common grid. Noon temperature was estimated as the maximum daily temperature minus 2.0 °C.

## FWI and Fire Season Length Calculations

Once the precipitation and humidity variables were calibrated to provide a point estimate at solar noon, the six standard indexes in the Canadian FWI System were generated. From FWI we calculated the daily severity rating (DSR), which is a measure of potential fire control difficulty and averaged this severity rating over the season (May to August) to get a seasonal severity rating (SSR). Average SSR was calculated for each time period and model. Means were also taken of temperature, RH, total seasonal rainfall, and SSR over the fire season. Ratios were determined for the $3\times CO_2$:$1\times CO_2$ scenarios of mean total seasonal rainfall and mean SSR. Temperature differences were taken between the $3\times CO_2$ and $1\times CO_2$ scenarios. Other

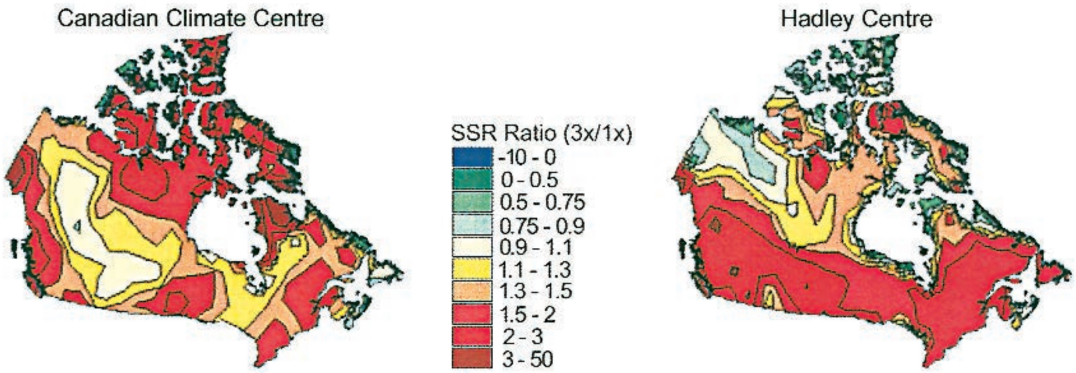

Figure 3. Ratio of $3\times CO_2$:$1\times CO_2$ mean seasonal (May to Aug) fire severity (SSR) from the Canadian Climate Centre's and Hadley Centre's General Circulation Models. Values were calculated for each grid cell and then interpolated over North America. Increases are shown in red. Decreases are shown in green. Little or no change is shown in yellow.

analysis included examining maximum and 90th percentile values of DSR at each gridpoint. Fire season length was calculated by taking the start of the season to be the point at which there were 3 consecutive days with an average maximum daily temperature above 3.5 °C. The end of the season was considered to be the first occurrence of that average dropping below 3.5 °C after 1 August.

## RESULTS

We displayed all weather variables and FWI System indexes spatially to look for patterns and to facilitate qualitative comparisons between the two models. Both models agreed closely on the $1\times CO_2$ temperature. When we looked at the difference between the $3\times CO_2$ and $1\times CO_2$ temperature scenarios the areas of greatest increases differed between the two models. The Hadley model illustrated the greatest temperature change in southern Canada with increases averaging 5–6 °C. The CCC model showed a large increase in temperatures at latitudes north of 55°N (<6 °C). Rainfall was different between the two models especially around the Canadian Rockies. Generally, the Hadley model was drier than the CCC model for both time periods, though the former showed a larger change, especially in the north where the model predicted increases in seasonal precipitation of 10%–50%. Not much insight was gained into future humidity, as there was little difference between the models or time periods. Both models showed an increase in SSR in the future, with the CCC model predicting higher SSR absolute values than the Hadley model. The ratio of $3\times CO_2$ SSR:$1\times CO_2$ SSR showed a much larger change in the Hadley model (Figure 3). The increase appeared to be double and in some areas more than triple the current SSR. The CCC model did not show as clear a change in SSR and predicted a different scenario than the Hadley model for much of central Canada. Both models depicted a longer fire season in Canada of a few days in the south up to approximately a month at

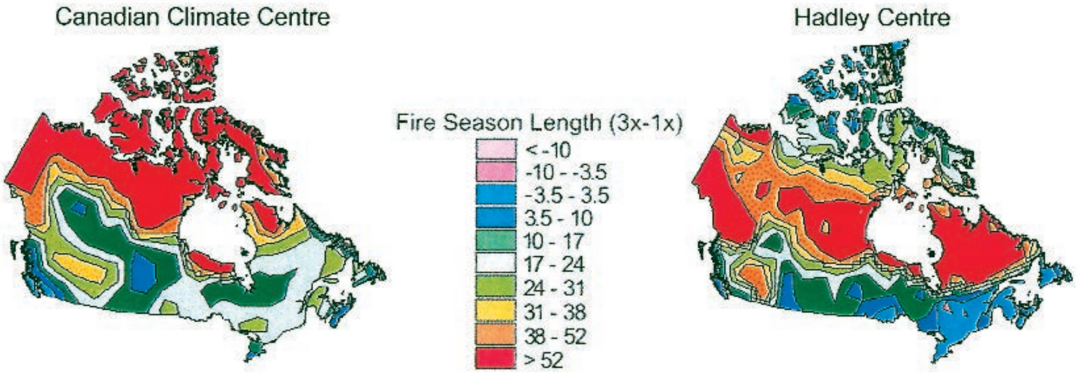

Figure 4. Change in fire season length from $1\times CO_2$ to $3\times CO_2$ from the Canadian Climate Centre's and Hadley Centre's General Circulation Models. Values in green represent an increase of 10 to 31 days in the fire season. Values in orange and red represent increases of greater than 31 days.

northerly latitudes (Figure 4) due mainly to warmer spring and fall temperatures. On average the fire season increased by approximately 2 to 3 weeks across Canada.

## DISCUSSION

The GCMs in this study suggest increases in SSR of up to 200% in some areas of Canada. These increases may or may not lead to increased fire occurrence under a $3\times CO_2$ climate. A study by Flannigan et al. (2000) of the Hadley and CCC GCMs under a $2\times CO_2$ climate suggests that SSR will increase by 10%–50% over most of North America though they point out there is much spatial variation, including areas of little change. This agrees well with our results, as it is not unreasonable to expect that the increases will be larger for the $3\times CO_2$ period than they are for the $2\times CO_2$ period. The study by Flannigan and Van Wagner (1991) of three different GCMs modeling the $2\times CO_2$ scenario predicts a 46% increase in SSR in Canada. They suggest this may lead to a proportional increase in area burned, though area burned depends on several factors including the number of fire ignitions and suppression efforts. The length of the fire season will also affect the area burned. We found the fire season to be increasing by an average of 2 to 3 weeks across much of Canada. These estimates might be conservative because the fire season analysis was constrained by our mechanistic criteria and time period. It is possible that in some situations we ended the fire season prematurely if, for example, there was a cold snap early in September but the rest of the month was relatively warm. According to our criteria, the fire season would have ended, though in reality the season may have gone on longer. This is not a problem in most of Canada where fire seasons usually fall between 1 April and 30 September. Wotton and Flannigan (1993) examined fire season length using the $2\times CO_2$ daily CCC GCM. They examined only forested areas of Canada and found the fire season length to be increasing by an average of 30 days. The main reason for the longer season were the increased temperatures described by the model as were also seen in the CCC GCM's $3\times CO_2$ run examined in this study. Stocks et al. (1998) also noticed an increase in SSR and an earlier start to the fire season while looking at several GCMs for the $2\times CO_2$ scenario. Many studies agree that future climate will be warmer leading to higher SSR values, but the impacts of this are not clear. Flannigan et al. (1998) point out that higher temperatures do not necessarily lead to higher fire frequency. Fire frequency actually decreased in some of their study areas despite warming since the Little Ice Age (ca. 1850). They speculate that may be due to increased precipitation in the areas of higher temperatures. It is clear that there are large spatial variations in fire weather and that no single conclusion can be reached for all of Canada. Many other factors such as ignitions and fire management policies must be considered when looking at the impact of climate change on the fire regime. Ignitions caused by humans may change in the future. Also in a warmer climate, lightning ignition probabilities may increase (Price and Rind 1994). Our analysis shows increasing fire danger and a longer fire season in the future for many regions of Canada.

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