# Climate change and wildfire in Canada

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Received July 24, 1990
Accepted August 13, 1990

FLANNIGAN, M. D., and VAN WAGNER, C. E. 1991. Climate change and wildfire in Canada. Can. J. For. Res. **21**: 66–72.

This study investigates the impact of postulated greenhouse warming on the severity of the forest fire season in Canada. Using $CO_2$ levels that are double those of the present ($2 \times CO_2$), simulation results from three general circulation models (Geophysical Fluid Dynamics Laboratory, Goddard Institute for Space Studies, and Oregon State University) were used to calculate the seasonal severity ratings for six stations across Canada. Monthly anomalies from the $2 \times CO_2$ simulation results were superimposed over historical sequences of daily weather. Then, seasonal severity ratings of the present were compared with those for $2 \times CO_2$ using five variations involving temperature, precipitation, and relative humidity. The relationship between seasonal severity rating and annual provincial area burned by wildfire was explored. The results suggest a 46% increase in seasonal severity rating, with a possible similar increase in area burned, in a $2 \times CO_2$ climate.

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La présente étude analyse l'impact reconnu de l'effet de serre sur l'intensité de la saison des incendies de forêts au Canada. À l'aide des niveaux de $CO_2$ qui se double à l'heure actuelle ($2 \times CO_2$), des résultats de simulation provenant de trois modèles généraux de circulation (Geophysical Fluid Dynamics Laboratory, Goddard Institute for Space Studies, Université de l'État d'Oregon) ont été utilisés pour calculer la cote dans six stations dispersées au Canada. Les anomalies, qui se présentaient chaque mois à la suite des simulations de $2 \times CO_2$, ont été appliquées aux séquences historiques des données météorologiques quotidiennes. Puis, les cotes d'intensité saisonnière actuelles ont été comparées à celles qui ont été obtenues par simulation ($2 \times CO_2$), en utilisant cinq variations qui comprenaient la température, la précipitation et l'humidité relative. Après quoi, le rapport a été établi entre la cote d'intensité saisonnière et la superficie des terres provinciales brûlées. Les résultats semblent indiquer une augmentation de 46% quant à la cote d'intensité saisonnière et une augmentation similaire concernant les superficies brûlées qui se trouverait dans un climat de $2 \times CO_2$.

## Introduction

A growing consensus exists that the Earth's climate will start warming at an unprecedented rate because of increasing amounts of radiatively active gases, such as water vapor, carbon dioxide, methane, ozone, nitrous oxide, and chlorofluorocarbons. According to predictions of various general circulation models (GCMs), the mean annual global temperature will rise by 1.5–5.0°C (Schlesinger and Mitchell 1987) as a result of a doubling of $CO_2$ ($2 \times CO_2$) alone. An effect equivalent to a doubling of $CO_2$ will take place by the year 2040 because of the added effect of other greenhouse gases.

The objective of this study is to interpret the potential impact of such warming on the severity of the forest fire season in Canada. To accomplish this, weather factors other than temperature, namely precipitation, relative humidity, and wind, and their influence on the fire regime, will also have to be taken into consideration.

Informal speculations about the potential future fire regime have appeared in various places, some suggesting dire consequences, but not much objective research has been reported. Street (1989), in his recent study dealing with Ontario, suggests a fire regime of increased length and severity under the two $2 \times CO_2$ scenarios he used. However, he dealt with weather as monthly averages, thus obscuring the dramatic daily variation in weather that affects fire incidence and behavior so strongly. Beer et al. (1988) tested the effect of potential climate change on Australian fire danger based on several modifications of the actual daily weather for a 22-year period at one location and concluded, in terms of mean annual variations, that the most significant weather parameter was relative humidity. Recently, Overpeck et al. (1990) suggested, based on climate-model results, that global warming favors increased rates of forest disturbance, including forest fires.

Recent trends in forest fire activity warn of potential trouble in the future. According to a recent study by Van Wagner (1988), the mean annual national burned area (computed as an exponential mean[1] with 10% weight on the current year) has increased from a minimum of 918 000 ha in 1968 to 2 016 000 ha in 1989 (Fig. 1), with 1989 producing the highest burned area on record (6 600 000 ha).

## Data and methods

In this study we used three GCMs: (*i*) Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Weatherald 1980), (*ii*) Goddard Institute for Space Studies (GISS) (Hansen et al. 1983, 1988), and (*iii*) Oregon State University (OSU) (Schlesinger and Zhao 1989).

Output from the GCMs was obtained from the National Center for Atmospheric Research (February 1988 release) via the Atmo-

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[1] The exponential mean is computed serially by adding one-tenth of the current annual burned area to nine-tenths of the previous year's exponential mean. This method of averaging assigns a weight of 0.1 to the current year, but this weight decreases by 10% as each year goes by. Thus, the last 10 years make up 65% of the weight, while the other 35% is spread out indefinitely into the past.

Printed in Canada / Imprimé au Canada

spheric Environment Services of Environment Canada. These outputs were in the form of monthly anomalies of temperature and precipitation for points on a grid system. The GCM designers ran their models for both a 2 × $CO_2$ case and a 1 × $CO_2$ case (i.e., the present normal). The temperature anomaly is then quoted as the difference between the 2 × $CO_2$ and 1 × $CO_2$ average monthly temperatures in degrees Celsius. The precipitation anomaly is given as the quotient of the 2 × $CO_2$ monthly estimate divided by the 1 × $CO_2$ value. The Atmospheric Environment Service Climate Centre Office then plotted the grid values of these anomalies and transformed the data to the form of monthly temperature and precipitation anomaly isolines as in the example of Fig. 2.

GCM modelers have made many compromises to keep the overall complexity at a manageable level, especially with respect to (*i*) the contribution of cloud to the Earth's albedo, (*ii*) the changing albedo of snow and sea ice, with changing temperatures, (*iii*) the physics of the ocean's role, (*iv*) the biological effects on hydrology, and (*v*) the coarseness of spatial resolution, to name a few. Schlesinger and Mitchell (1987) note that simulation confidence is greater for temperature than for precipitation in their overview of present-day GCMs. The quality of regional simulations is suspect (Grotch 1988). Nevertheless, despite their shortcomings, in our judgement GCMs simulate present-day circulation and temperature patterns with sufficient accuracy when averaged over the hemisphere to warrant their use for present purposes.

As a measure of the effects of climate change on forest fires, the seasonal severity rating (SSR) has been calculated using the 2 × $CO_2$ scenarios. The SSR is a component of the Canadian Forest Fire Weather Index (FWI) System[2] (Van Wagner 1987). The SSR is simply an average of the daily severity rating (DSR), which, in turn, is computed directly from the Fire Weather Index

$$\text{DSR} = 0.0272(\text{FWI})^{1.77}$$

The FWI represents the relative intensity of a spreading fire and is well suited to the daily representation of fire danger at a point, but should be used as its single value only. The daily severity rating was designed to be a better measure of the work needed to suppress a fire than the FWI and is recommended for temporal or spatial averaging of fire danger for management purposes (Van Wagner 1970*a*).

In this study, the GCMs' anomalies were used together with historical observations of daily weather to calculate SSRs for a 2 × $CO_2$ scenario. This allowed a comparison of historical SSRs and the 2 × $CO_2$ SSRs. Then, historical SSRs were related to the annual area burned in a province to see if changes in area burned can be related to changes in SSR, thereby giving an indication of the area that would be burned in a 2 × $CO_2$ climate.

As test sites, six stations were selected across Canada representing a wide range of climate and forest types (Table 1). The appropriate temperature and precipitation anomaly values were then abstracted, with the help of interpolation, from Atmospheric Environment Service maps (Table 2). Fire weather data, composed of noon observations of temperature, relative humidity, wind speed, and 24-h rainfall, were available for each station for the years 1953–1987. Computations of the daily FWI and daily severity rating began on April 1, but only those of the period May 1 to August 31 were averaged to obtain the SSRs for each station and year.

FIG. 1. Graph of the burned area in Canada using an exponential mean with a weight of 0.1 on the current year plotted over the current year. (For details on the exponential mean please see footnote 1 in the text.)

From the 35 years covered in this study, those years for each station with the highest and lowest SSRs were selected, and also a year with a SSR close to the mean. The resultant set of 18 SSRs, three for each of the six stations, constituted a range (base line) for the effect of climate on forest fire severity against which climate change could be compared.

As already described, we used the scenarios from the three GCMs with monthly climatic anomalies of temperature and precipitation, thus having no indication of the potential variation in day to day weather. Therefore, it has been assumed in this study that historical daily weather patterns will simply continue. The predicted monthly anomalies have been superimposed onto the chosen three sets of daily fire weather in five ways: (*i*) TEMP, the monthly temperature anomaly is added to each daily temperature; (*ii*) PREC, the monthly precipitation anomaly is applied as a multiplication factor to the daily precipitation amounts (if any); (*iii*) TPREC, both the temperature and the precipitation are modified daily as in *i* and *ii*; (*iv*) TRH, the temperature is modified as in *i* and then the relative humidity is recalculated daily based on the new temperature and the present dew point[3]; and (*v*) TRHP, all three variables (temperature, precipitation, and relative humidity) are modified as in *i*, *ii*, and *iv*.

In each of these five variations, all weather variables not mentioned remain unchanged (including wind speed, which was not part of this test). This straightforward approach to reconstructing daily weather implies two major assumptions, namely that (*i*) the daily variability in all aspects of weather remains constant and (*ii*) the 1 × $CO_2$ model simulations represent the present climate. Burning that occurs during the 4 months of May to August currently accounts for 95% of Canada's burned area (Harrington 1982). By confining our attention to these months, we have not

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[2] The FWI System comprises three moisture codes and two intermediate indexes. The three moisture codes represent the moisture content of fine fuels (Fine Fuel Moisture Code), loosely compacted duff (Duff Moisture Code), and compact organic soil (Drought Code). The two intermediate indexes, which are derived from the moisture codes and the surface wind, indicate the rate of initial fire spread (Initial Spread Index) and total available fuel (Build Up Index). The two intermediate indexes are combined to obtain the FWI, which represents the intensity of the spreading fire.

[3] We do not necessarily believe that the dew point temperature will remain constant while the air temperature increases. However, this variation along with the variation that allows relative humidity to remain constant gives us a range of relative humidity so that we can gauge the sensitivity of the SSR to relative humidity.

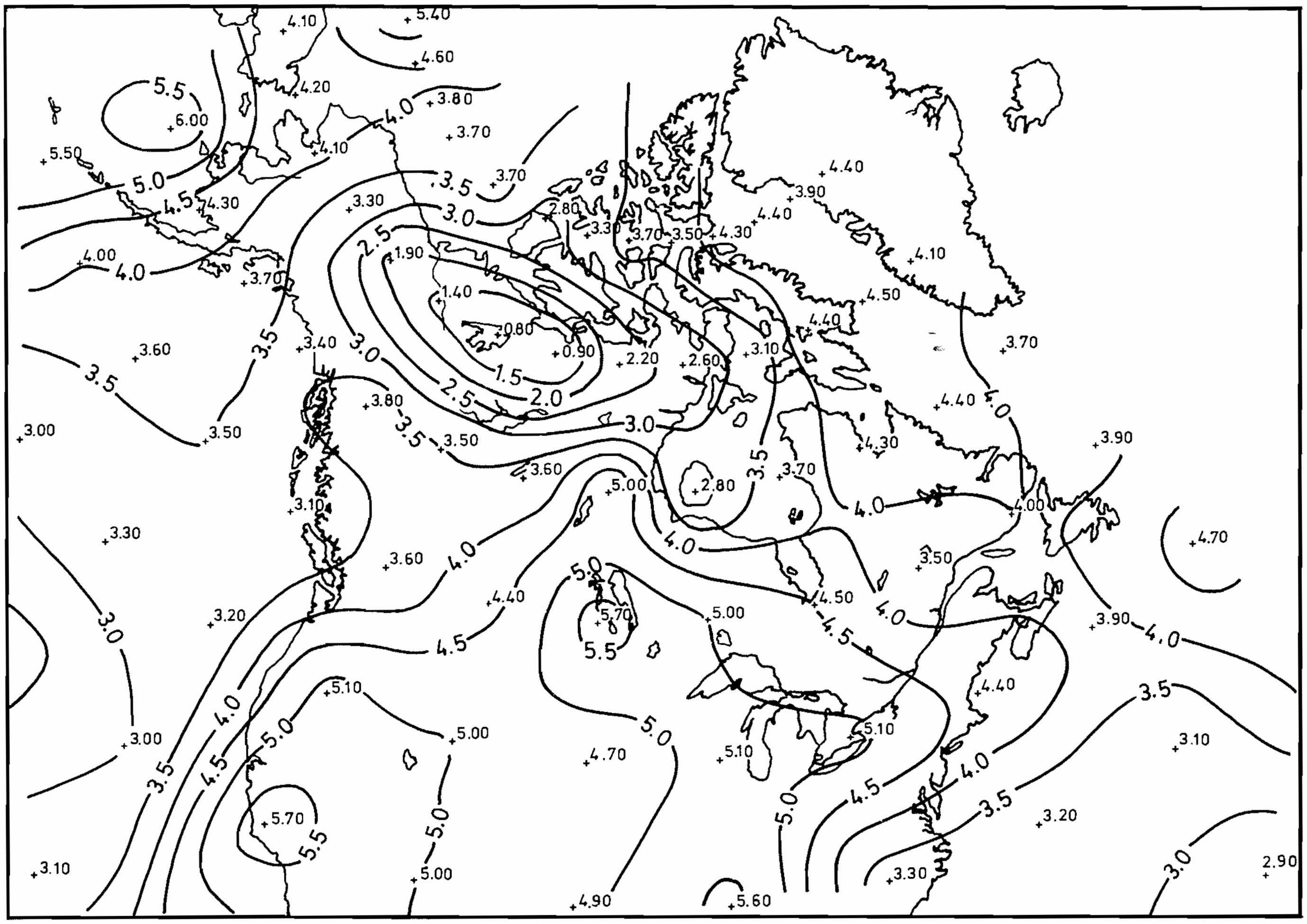

FIG. 2. April temperature anomaly (°C) for a 2 × $CO_2$ run minus the 1 × $CO_2$ run using the GISS model.

considered the likelihood of a longer fire weather season or the possibility of increased dryness in the early spring, but we have based our comparison on the period most active under the past climate.

Accordingly, the temperature and precipitation anomalies for May to August (plus April as the lead-in period) were applied to the 18 sets of weather data, producing one new set of resultant SSRs for each weather variation and GCM.

For each of the six sites, the relation between SSR and the annual provincial area[4] burned was examined for the period 1953–1980. A simple linear regression was employed to see how much variance is explained by the SSR. The coefficient for the SSR in the regression equation reflects the sensitivity of area burned to SSR.

## Results and discussion

### *SSR and weather*

The SSR results are presented in Tables 3–5 for the three GCMs. Each Table lists the base-line SSRs derived from the 3 identified years of weather data for each station and the ratios of the forecast SSR to the base-line SSR for each climate variation described earlier (i.e., TEMP, PREC, TPREC, TRH, and TRHP).

TABLE 1. Stations and their locations

| Station | Latitude (N) | Longitude (W) |
|---|---|---|
| Cranbrook, British Columbia | 49°37′ | 115°47′ |
| Fort Smith, Northwest Territories | 60°01′ | 111°58′ |
| Hudson Bay, Saskatchewan | 52°49′ | 102°19′ |
| Sioux Lookout, Ontario | 50°07′ | 91°54′ |
| PNFI,* Ontario | 46°01′ | 75°27′ |
| Fredericton, New Brunswick | 45°52′ | 66°32′ |

*Petawawa National Forestry Institute, Chalk River, Ontario. Data from Killaloe, for the period 1953–1958, were used to complete the PNFI record.

Table 6 lists the 3-year average ratio of the SSR divided by the base-line SSR for all models for each station and for all stations combined. The results show that there are significant differences among the models. The GFDL seasonal severity rating results are considerably higher than those of the other two models. This is obviously the result of the significantly higher temperature anomalies of the GFDL. Geographically there appears to be little difference in the increase in the SSR for each model, except that the GFDL shows a more pronounced increase over central Canada (Sioux Lookout in particular). Generally, the percent SSR increases were greatest for the lowest SSR values.

It is recognized that any fire danger index can only

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[4] Provincial areas for this study included British Columbia, the Yukon and Northwest territories combined, Saskatchewan, western Ontario (west of Lake Nipigon), eastern Ontario, and the combined Atlantic Provinces.

TABLE 2. Temperature and precipitation data

| GCM, station | April |  | May |  | June |  | July |  | August |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | TA | PPN | TA | PPN | TA | PPN | TA | PPN | TA | PPN |
| GFDL |  |  |  |  |  |  |  |  |  |  |
| Cranbrook | 6.7 | 1.20 | 4.7 | 1.15 | 5.8 | 0.72 | 7.2 | 1.00 | 6.1 | 1.20 |
| Fort Smith | 0.1 | 1.47 | 10.0 | 1.15 | 8.1 | 1.30 | 5.3 | 1.05 | 5.5 | 0.75 |
| Hudson Bay | 9.7 | 1.21 | 6.2 | 1.05 | 8.2 | 0.90 | 7.8 | 0.75 | 7.2 | 0.80 |
| Sioux Lookout | 8.1 | 0.90 | 4.6 | 0.82 | 9.1 | 0.75 | 8.9 | 0.80 | 8.0 | 0.70 |
| PNFI* | 6.0 | 0.77 | 4.2 | 1.30 | 6.5 | 0.90 | 8.4 | 0.70 | 6.2 | 1.15 |
| Fredericton | 5.6 | 0.95 | 4.7 | 1.45 | 4.6 | 1.15 | 6.2 | 0.90 | 6.0 | 0.78 |
| GISS |  |  |  |  |  |  |  |  |  |  |
| Cranbrook | 4.1 | 1.15 | 3.2 | 1.20 | 3.4 | 1.21 | 2.4 | 1.17 | 4.2 | 1.20 |
| Fort Smith | 3.3 | 1.30 | 3.8 | 1.27 | 3.4 | 1.40 | 2.7 | 1.40 | 3.1 | 1.30 |
| Hudson Bay | 5.1 | 1.10 | 3.3 | 1.09 | 3.1 | 1.13 | 3.1 | 1.20 | 2.5 | 1.18 |
| Sioux Lookout | 5.1 | 1.08 | 1.9 | 0.90 | 3.5 | 1.27 | 2.8 | 1.00 | 2.9 | 1.30 |
| PNFI* | 4.7 | 1.08 | 3.6 | 1.13 | 3.2 | 1.03 | 3.5 | 1.20 | 3.5 | 1.20 |
| Fredericton | 4.0 | 1.00 | 4.2 | 1.27 | 3.4 | 0.93 | 3.2 | 1.00 | 3.2 | 1.05 |
| OSU |  |  |  |  |  |  |  |  |  |  |
| Cranbrook | 3.6 | 1.31 | 2.6 | 1.01 | 3.4 | 1.21 | 3.0 | 0.98 | 2.3 | 1.21 |
| Fort Smith | 3.9 | 1.15 | 3.3 | 1.01 | 3.4 | 1.06 | 3.7 | 0.95 | 3.4 | 0.80 |
| Hudson Bay | 3.7 | 1.23 | 3.1 | 0.93 | 3.6 | 1.09 | 3.4 | 1.05 | 3.0 | 1.25 |
| Sioux Lookout | 2.6 | 0.95 | 3.4 | 0.90 | 4.2 | 0.98 | 3.6 | 1.15 | 3.8 | 1.00 |
| PNFI* | 1.6 | 1.00 | 3.6 | 1.01 | 3.9 | 0.90 | 3.2 | 1.10 | 3.2 | 1.05 |
| Fredericton | 1.8 | 1.13 | 3.1 | 1.05 | 3.6 | 1.00 | 3.3 | 0.90 | 3.4 | 1.10 |

NOTE: TA is the monthly mean temperature anomaly (°C); PPN is the precipitation as a proportion of normal values.
*Petawawa National Forestry Institute.

respond to climate change according to the weather effects built into its equations. The weather variables used in the FWI System are temperature, relative humidity, wind speed, and precipitation. For present purposes, temperature is obviously the most important of the four variables because only large positive increases are predicted. Relative humidity, when a constant dew point is assumed, is also important because its change is downward only. Wind speed is not adjusted in the present study and is, therefore, not examined. Precipitation effects in the FWI System are complex; however, the forecast anomalies range both upward and downward from present levels.

Temperature and relative humidity enter into the FWI System through effects on the drying phase of its three moisture codes (Fine Fuel Moisture Code, Duff Moisture Code, and Drought Code) as described by Van Wagner (1987). In each code, drying after rain is a negative exponential function whose logarithmic slope increases with rising temperature and (for the Fine Fuel and Duff moisture codes) with falling relative humidity. The three moisture codes have time lags (defined as time to 1/e of the potential moisture change) in normal weather (21.1°C, 45% relative humidity) as follows: Fine Fuel Moisture Code, 2/3 day; Duff Moisture Code, 12 days; and Drought Code, 52 days. The magnitude of their effects on the FWI is the reverse order of the time lag; thus, the Fine Fuel Moisture Code, which reacts most quickly to day to day weather, has the greatest effect on the FWI, and so on. The Fine Fuel Moisture Code, in addition, dries to a variable equilibrium moisture content, which is also dependent on temperature and relative humidity. All these effects are listed in Table 7.

TABLE 3. Base-line SSR and ratios (SSR forecast/SSR base line) for various scenarios: GFDL model

| Station and year | Base-line SSR | SSR ratios |  |  |  |  |
|---|---|---|---|---|---|---|
|  |  | TEMP | PREC | TPREC | TRH | TRHP |
| Cranbrook |  |  |  |  |  |  |
| 1958, max. | 16.98 | 1.30 | 0.99 | 1.30 | 1.80 | 1.79 |
| 1971, mean | 6.27 | 1.48 | 0.98 | 1.47 | 2.37 | 2.35 |
| 1980, min. | 1.12 | 1.82 | 0.97 | 1.79 | 3.46 | 3.44 |
| Fort Smith |  |  |  |  |  |  |
| 1971, max. | 8.81 | 1.57 | 0.96 | 1.54 | 2.79 | 2.72 |
| 1979, mean | 4.55 | 1.86 | 0.93 | 1.75 | 3.41 | 3.25 |
| 1974, min. | 1.62 | 2.04 | 0.94 | 1.94 | 4.79 | 4.55 |
| Fredericton |  |  |  |  |  |  |
| 1960, max. | 4.09 | 1.54 | 0.99 | 1.52 | 2.71 | 2.68 |
| 1972, mean | 2.42 | 1.55 | 0.95 | 1.48 | 2.86 | 2.75 |
| 1981, min. | 1.00 | 1.70 | 1.05 | 1.77 | 3.76 | 3.92 |
| Hudson Bay |  |  |  |  |  |  |
| 1961, max. | 9.02 | 1.55 | 1.05 | 1.60 | 2.69 | 2.74 |
| 1955, mean | 3.15 | 1.75 | 1.10 | 1.89 | 3.92 | 4.13 |
| 1983, min. | 1.11 | 2.14 | 1.13 | 2.35 | 5.33 | 5.91 |
| PNFI* |  |  |  |  |  |  |
| 1975, max. | 4.33 | 1.53 | 1.06 | 1.62 | 2.73 | 2.88 |
| 1976, mean | 1.70 | 1.72 | 1.01 | 1.72 | 3.75 | 3.79 |
| 1973, min. | 0.76 | 1.88 | 1.04 | 1.96 | 4.62 | 4.83 |
| Sioux Lookout |  |  |  |  |  |  |
| 1981, max. | 4.45 | 1.74 | 1.12 | 1.91 | 3.41 | 3.73 |
| 1956, mean | 2.03 | 2.12 | 1.24 | 2.52 | 5.02 | 5.90 |
| 1969, min. | 0.59 | 2.41 | 1.27 | 2.95 | 7.08 | 8.88 |

*Petawawa National Forestry Institute.

The rationale for the development of the moisture codes to depict the effects of temperature and relative humidity on forest fuels may be found in Beall (1948) and Van Wagner (1972, 1979) for the Fine Fuel Moisture Code, Van Wagner (1970*b*) for the Duff Moisture Code, and Turner (1972) for the Drought Code. These authors depended mainly on the analysis of empirical field data, backed up by laboratory evidence and physical theory. Because of its partly empirical

TABLE 4. Base-line SSR and ratios (SSR forecast/SSR base line) for various scenarios: GISS model

| Station and year | Base-line SSR | SSR ratios | | | | |
|---|---|---|---|---|---|---|
| | | TEMP | PREC | TPREC | TRH | TRHP |
| Cranbrook | | | | | | |
| 1958, max. | 16.98 | 1.17 | 0.95 | 1.12 | 1.44 | 1.38 |
| 1971, mean | 6.27 | 1.27 | 0.93 | 1.19 | 1.72 | 1.61 |
| 1980, min. | 1.12 | 1.45 | 0.87 | 1.27 | 2.16 | 1.89 |
| Fort Smith | | | | | | |
| 1971, max. | 8.81 | 1.23 | 0.87 | 1.10 | 1.68 | 1.51 |
| 1979, mean | 4.55 | 1.33 | 0.82 | 1.11 | 1.85 | 1.56 |
| 1974, min. | 1.62 | 1.40 | 0.78 | 1.10 | 2.20 | 1.75 |
| Fredericton | | | | | | |
| 1960, max. | 4.09 | 1.32 | 0.98 | 1.30 | 1.95 | 1.92 |
| 1972, mean | 2.42 | 1.38 | 0.96 | 1.33 | 2.13 | 2.06 |
| 1981, min. | 1.00 | 1.40 | 0.99 | 1.39 | 2.44 | 2.42 |
| Hudson Bay | | | | | | |
| 1961, max. | 9.02 | 1.22 | 0.93 | 1.15 | 1.60 | 1.52 |
| 1955, mean | 3.15 | 1.27 | 0.92 | 1.17 | 1.89 | 1.75 |
| 1983, min. | 1.11 | 1.40 | 0.88 | 1.24 | 2.23 | 1.95 |
| PNFI* | | | | | | |
| 1975, max. | 4.33 | 1.29 | 0.95 | 1.22 | 1.84 | 1.75 |
| 1976, mean | 1.70 | 1.37 | 0.91 | 1.25 | 2.17 | 1.98 |
| 1973, min. | 0.76 | 1.42 | 0.92 | 1.30 | 2.46 | 2.28 |
| Sioux Lookout | | | | | | |
| 1981, max. | 4.45 | 1.27 | 0.93 | 1.20 | 1.72 | 1.62 |
| 1956, mean | 2.03 | 1.37 | 0.94 | 1.29 | 2.05 | 1.93 |
| 1969, min. | 0.59 | 1.41 | 0.95 | 1.34 | 2.32 | 2.17 |

*Petawawa National Forestry Institute.

TABLE 5. Base-line SSR and ratios (SSR forecast/SSR base line) for various scenarios: OSU model

| Station and year | Base-line SSR | SSR ratios | | | | |
|---|---|---|---|---|---|---|
| | | TEMP | PREC | TPREC | TRH | TRHP |
| Cranbrook | | | | | | |
| 1958, max. | 16.98 | 1.14 | 0.97 | 1.11 | 1.35 | 1.32 |
| 1971, mean | 6.27 | 1.22 | 0.95 | 1.16 | 1.57 | 1.50 |
| 1980, min. | 1.12 | 1.39 | 0.90 | 1.27 | 1.99 | 1.81 |
| Fort Smith | | | | | | |
| 1971, max. | 8.81 | 1.25 | 1.01 | 1.26 | 1.74 | 1.75 |
| 1979, mean | 4.55 | 1.35 | 1.00 | 1.36 | 1.93 | 1.95 |
| 1974, min. | 1.62 | 1.41 | 1.03 | 1.45 | 2.31 | 2.38 |
| Fredericton | | | | | | |
| 1960, max. | 4.09 | 1.30 | 1.00 | 1.31 | 1.91 | 1.93 |
| 1972, mean | 2.42 | 1.32 | 1.00 | 1.31 | 1.98 | 1.98 |
| 1981, min. | 1.00 | 1.38 | 1.03 | 1.43 | 2.38 | 2.43 |
| Hudson Bay | | | | | | |
| 1961, max. | 9.02 | 1.23 | 0.97 | 1.20 | 1.65 | 1.62 |
| 1955, mean | 3.15 | 1.29 | 0.96 | 1.24 | 1.99 | 1.91 |
| 1983, min. | 1.11 | 1.42 | 0.93 | 1.33 | 2.35 | 2.19 |
| PNFI* | | | | | | |
| 1975, max. | 4.33 | 1.28 | 0.99 | 1.27 | 1.83 | 1.82 |
| 1976, mean | 1.70 | 1.35 | 0.99 | 1.35 | 2.15 | 2.14 |
| 1973, min. | 0.76 | 1.41 | 0.97 | 1.37 | 2.39 | 2.34 |
| Sioux Lookout | | | | | | |
| 1981, max. | 4.45 | 1.33 | 0.99 | 1.32 | 1.93 | 1.92 |
| 1956, mean | 2.03 | 1.44 | 0.99 | 1.42 | 2.35 | 2.32 |
| 1969, min. | 0.59 | 1.56 | 0.98 | 1.56 | 2.88 | 2.90 |

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TABLE 6. Average base-line SSRs and ratios (SSR forecast/SSR base line) for each scenario, combining the three GCMs and all 3-years' fire weather, by individual station and for all stations

| Station | Base-line SSR | Average SSR ratios | | | | |
|---|---|---|---|---|---|---|
| | | TEMP | PREC | TPREC | TRH | TRHP |
| Cranbrook | 8.12 | 1.36 | 0.95 | 1.30 | 1.99 | 1.90 |
| Fort Smith | 4.99 | 1.50 | 0.93 | 1.40 | 2.52 | 2.38 |
| Fredericton | 2.50 | 1.43 | 0.99 | 1.43 | 2.46 | 2.45 |
| Hudson Bay | 4.43 | 1.47 | 0.98 | 1.47 | 2.63 | 2.64 |
| PNFI* | 2.26 | 1.47 | 0.99 | 1.45 | 2.66 | 2.64 |
| Sioux Lookout | 2.36 | 1.60 | 1.05 | 1.72 | 3.20 | 3.48 |
| All stations | 4.11 | 1.47 | 0.98 | 1.46 | 2.58 | 2.58 |

*Petawawa National Forestry Institute.

basis, the Canadian FWI System appears to be well structured and suited to studies of the potential fire effects of climate change, at least within Canada itself.

The influence of temperature and relative humidity, as well as precipitation, can be seen in the SSR results. Rising temperature alone causes increases of 14–56% above the base-line SSR for the GISS and OSU models, and 30–141% for the GFDL model. The higher percent increases from the GFDL model compared with the other two models are due to the much larger temperature anomalies computed by the GFDL model for all six stations.

The role of relative humidity is certainly important. Beer et al. (1988) report that bush-fire danger in Australia under changing climatic regimes was most sensitive to changes in relative humidity. However, their results may be biased by the relative lack of temperature sensitivity in the Australian Forest Fire Danger Index or by the small range of temperature data used in their study. If dew points are held constant and the relative humidity recalculated using the GCM temperatures, the relative humidity drops and the SSR increase significantly. However, holding the relative humidity constant may more accurately portray the daily weather in a warmer climate. The GCM precipitation for most regions and months increases along with temperature and evapotranspiration, which, in turn, should allow the relative humidity to remain relatively unchanged. Indeed, Rind (1986) found that the relative humidity tended to remain constant when simulating warm and cold climates using the GISS model.

Wind speed was left unchanged. There are arguments for both higher and lower wind speeds. Higher wind speeds might be realized through more intense convective storms because the atmosphere is becoming more unstable as a result of higher surface temperatures and a cooler but higher tropopause. However, one could also argue that temperature contrasts between the pole and the equator will be reduced, thereby lowering the energy available for synoptic-scale disturbances and the winds accompanying them.

The forecast precipitation anomalies (in which confidence is quite low) turn out to have little impact on the SSR. Two factors help explain this result. First, precipitation amounts increase for most stations. Second, the distribution of precipitation events is held to observed sequences from past years. This is a critical factor. Will the frequency of drought increase with greenhouse warming? Flannigan and Harrington (1988) found that the monthly provincial area burned in Canada was strongly influenced by long sequences of days without rain (<1.5 mm), thus confirming the generally known principle that sequence of precipitation events is more important for explaining burned area than cumulative precipitation amount. They also suggested that the long

TABLE 7. Temperature and relative humidity (RH) effects in the FWI System moisture codes

| | Drying rate effect | | Equilibrium moisture content effect | |
|---|---|---|---|---|
| Code* | % increase per °C[†] | % increase per RH point[‡] | Decrease per °C | Increase per RH point[§] |
| FFMC | 3.7 | 3.2 | 0.18 | 0.20 |
| DMC | 4.5 | 2.2 | No effect | No effect |
| DC | 2.5 | No effect | No effect | No effect |

*FFMC, Fine Fuel Moisture Code; DMC, Duff Moisture Code; DC, Drought Code.

[†] Percent increase in negative exponential drying rate per degree Celsius over the range 10–30°C, based on the value at 20°C.

[‡] Percent increase in negative exponential drying rate per RH point over the range 70–20% RH, based on the value at 45%.

[§] Between 20 and 70% RH.

TABLE 8. Regression equations and explained variance for the relative provincial area burned by wildfire using the SSR for each station

| Province | Station | Statistic | Results |
|---|---|---|---|
| British Columbia | Cranbrook | Area equation | −0.614+0.288SSR |
| | | Standard error | 0.578, 0.078 |
| | | Variance explained | 0.34 |
| Yukon and Northwest territories | Fort Smith | Area equation | 0.059+0.271SSR |
| | | Standard error | 0.648, 0.138 |
| | | Variance explained | 0.13 |
| Saskatchewan | Hudson Bay | Area equation | −0.534+0.561SSR |
| | | Standard error | 0.642, 0.180 |
| | | Variance explained | 0.27 |
| W. Ontario | Sioux Lookout | Area equation | −0.921+1.077SSR |
| | | Standard error | 1.013, 0.459 |
| | | Variance explained | 0.18 |
| E. Ontario | PNFI* | Area equation | 1.20−0.020SSR |
| | | Standard error | 0.754, 0.298 |
| | | Variance explained | 0.00 |
| Atlantic Provinces | Fredericton | Area equation | 0.332+0.375SSR |
| | | Standard error | 1.566, 0.629 |
| | | Variance explained | 0.01 |

NOTE: The original area-burned data in hectares have been converted to a relative measure by dividing each monthly figure by the average monthly burned area for each province during the 1953–1980 period.

*Petawawa National Forestry Institute.

periods of dry weather were the product of upper atmosphere blocking ridges. Bates and Meehl (1986) found that the frequency of blocking was unchanged in the Northern Hemisphere when using the National Center for Atmospheric Research general circulation model 2 × $CO_2$ simulation. Thus, by using present daily weather patterns in this study, it is implicitly assumed that the frequency of blocking ridges will remain unchanged.

Which, if any, of the five variations in daily weather used in this study might be considered the most plausible? We believe that the modification that includes the temperature and precipitation anomalies, but holds relative humidity constant (namely TPREC) is the preferred choice, for various reasons given earlier. As for a choice of GCM, we merely note the relatively conservative pattern portrayed independently by both the GISS and OSU models compared with the more extreme GFDL result. However, objective criteria for a preference are beyond our present scope. Thus, a potential increase in SSR of some 46% (the three-model mean TPREC result from all stations, and years in Table 6) could be taken, with all its limitations, as our simple most plausible result. It is interesting to note that changing the climate in this study has the greatest effect on the minimum base-line year. Thus, not only could there be a shift to higher SSRs but also the shape of the frequency distribution could change as well.

### *SSR and burned area*

The interpretation of increased SSR in terms of fire activity, especially burned area, is a complex problem. The SSR, representing weather, is only one of the three main factors affecting burned area. The other two factors are ignition frequency and fire control activity. Obviously, if the other factors are equal, more severe fire weather will result in more burned area. However, the ignition rate is not necessarily well correlated with weather, and greater fire control effort may offset more severe weather to some unknown extent. A good regression of SSR versus burned area merely indicates that variations in weather have affected the historical burned area record; a poor regression is more difficult to interpret.

The relationship between burned area and the FWI System was examined by Harrington et al. (1983) using monthly burned areas from 1953 to 1980 for nine major divisions of Canada, with three to five stations representing the weather in each. They found generally poor correlation, as more or less expected, with explained variance from near 0 to 42% (increasing from east to west). However, their regression equations were not directly usable in the present study because they included components of the FWI System other than SSR (or its monthly form) in each analysis. For present purposes the same monthly burned-area data (combined into seasonal totals) were correlated with the base-line SSRs for each of the six study stations, of course linking each station with its appropriate provincial data for 1953 to 1980. The results are listed in Table 8. The same generally poor relationship found by Harrington et al. (1983) is obvious ($R^2$-values of 0 to 0.34), with the same tendency to increase from east to west. Also, the same authors found that western Canada accounted for 85% of the nation's burned area during 1953 to 1980, implying that any increase in burned area due to climate change may be sustained more by western Canada than by eastern Canada.

On the assumption that the relationship between SSR and burned area is linear, as shown in Table 8, and ignoring the $\alpha$ coefficients in the regression equations, this same ratio indicates a potential 46% increase in burned area. Or, if it were assumed that all the increase will take place west of Lake Nipigon, then the mean TPREC ratio of the four western stations in Table 6, namely 1.40, suggests an increase of 40%. Beyond this, no further regional analysis is attempted here.

There are other changes that could also have an important bearing on burned area. The length of the fire season might increase, with spring coming earlier in the year and fall coming later in the year. The quantity of available fuel may vary as a result of the changed climate or elevated $CO_2$ levels and directly affect fire intensity. Forest species composition may change because of climate change, and the changing composition may, in turn, be influenced by fire.

The relationships between burned area and SSR revealed in this study suggest a possible 40% or so increase in national burned area. The average national burned area has already increased more than 50% since 1970 (Van Wagner 1988). Is this increase a result of greenhouse warming or is it part of the natural variability of climate and associated area burned? We believe that it is too early to decide this question with any certainty. However, the potential effect of climate change on the Canadian forest fire regime, in both the economic and ecological senses, certainly deserves continuing attention.

## Summary

This study has shown that the SSR may increase 40% or so under an equivalent 2 × $CO_2$ climate, with the area burned increasing by a similar amount. If the frequency of drought increases or relative humidities are lowered, much greater increases are possible. These increases would not necessarily wreak havoc on Canadian forests. Fire has been an integral part of the natural system for millennia, and fire frequency and intensity have always varied with the climate.

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