University of Alberta

Climate Change and Fire Danger

by

Gregory James Baxter ©

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Name of Author: ͻregory James Baxter

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Greg Baxter

#2 14924-56 avenue
Edmonton, Alberta
T6H-4X9

February 6 1995

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled *Climate Change and Fire Danger* submitted by *Gregory James Baxter* in partial fulfillment of the requirements for the degree of *Master of Science*.

Dr. Dave Halliwell

Dr. Ian Campbell

Dr. [illegible] M. Woodard

February 3, 1995

ABSTRACT

A relationship exists between fire frequency, intensity, and severity, and climatic influences such as temperature, precipitation, humidity, and wind. Research on the 'drying process' of forest fuels, using a 1-d physical evaporation model initialised for a boreal forest environment, and the existing Canadian Forest Fire Danger Rating System (CFFDRS), will allow the importance of these meteorological variables in the fire/climate relationship to be determined.

The objective of this study is to determine the effects of climate change on fire danger in the boreal forest. Both models estimate fuel moisture conditions. Changes in fire danger were investigated using sensitivity tests altering various climatological variables to determine the influence on fire danger.

Results show soil moisture contents declining 3-4% depending on the type of fire season under a climate change scenario. Both models were sensitive to the same climatological influences (in order of influence); temperature, precipitation and humidity, wind speed (and Q*, in the evaporation model).

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CHAPTER 1

1.1 Introduction

The possibility of climate change has initiated research in fields where the potential exists for large impacts on the environment. Forest fire research is one of those fields. Present day General Circulation Models (GCMs) predict a 1.5 -4.5°C rise in mean global surface temperatures over the next 50 - 75 years (IPPC 1990), based on current and projected future levels of carbon dioxide (CO_2) in the atmosphere. GCMs are estimating greater warming closer to the poles, and thus the boreal region, and changes in precipitation and surface moisture conditions.

A relationship exists between fire frequency, intensity, and severity and such climatological influences as: temperature, precipitation, humidity, and wind. The relationship suggests that warmer and drier environments will produce drier fuels causing increased fire danger.

Forestry Canada uses the term 'fire danger' as a measure of the fixed and variable factors of the fire environment. Fire danger is determined by the ease of ignition, rate of spread, ease of control and the total fire impact (Merrill and Alexander 1987). It differs from 'fire hazard', an estimate of fuel availability, which does not incorporate a 'risk component'. The risk component is a source of ignition, such as lightning, spontaneous combustion, and human-caused fires.

Fuel condition (or availability) is assessed by the Fire Weather Index (FWI), which is a component of the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks *et al.* 1989). The CFFDRS has empirically derived the FWI to account for the effects of weather, latitude and season (month) on fuel moisture and fire behavior. This system has been under development since 1968, and is continuing to be adapted for use in all fuel types.

The drying process of forest fuels ultimately involves evaporation and a physically based model is appropriate for use in a situation where complex interactions are present. The model used in this study was developed by Halliwell (1989), and is hereafter referred to as the Halliwell model. It is a one-dimensional physical evaporation numerical model which simulates the surface energy balance, including evaporation. It is useful for complex situations such as in the surface boundary, where climatic feedback processes are common.

The Halliwell model is based on the physical boundary layer relationships that occur at the earths surface, and enables the user to alter climatic and environmental parameters to determine their importance in the energy balance. The energy balance for a particular site is determined by

$$Q^{*} = QH + QE + Qg \qquad (1.1)$$

where:

Q^{*} = Net radiation

QH = Sensible Heat flux

QE = Latent Heat flux

Qg = Soil Heat flux

The partitioning of Q^{*} into the three fluxes; QH, QE, and Qg, allows one to determine evaporation rates (Oke 1987); all units in Wm^{-2}.

The Halliwell model attempts to clarify relationships between variables selected by the user. An individual process can be isolated to discover its relative importance within the modelled system. It facilitates a quantitative prediction by simulating the local response to climate change and the forecasting of related changes in fire danger.

The FWI model can be run with historic fire weather as input, and allows a study of fire danger for various types of fire seasons. Selected periods identified using the FWI model can then be used in the Halliwell model to quantify the physical relationships between climatic parameters.

Eighty two percent of Canada's forested lands is boreal forest. The boreal forest is a fire-prone ecosystem - a mosaic of different-aged stands - resulting from fire activity (Rowe 1977). A rise in temperatures and a change in surface moisture conditions may affect the forest environment.

1.2 Objectives

The main objective of this study was to estimate the effects of climate change on fire danger in the boreal forest region of Canada. This was done by:

1) validating the Fire Weather Index model with fuel moisture samples gathered in the field. These relationships can then be used to estimate changes in fire danger from historic weather data.

2) Initializing and testing the Halliwell model for use in a boreal forest environment.

3) Determining the most likely scenario of future climate at a regional scale. This was done using existing General Circulation Model output and techniques developed for regional scale impact assessments (Robock *et al.* 1993).

4) Identifying changes in fire danger in response to altered climatological influences by performing sensitivity analysis using the Halliwell model.

1.3 Atmospheric General Circulation Models

The use of GCMs to simulate a possible range of climate change has increased over the last 20 years. GCMs are mathematical models, based on the laws of physics, that behave in a manner similar to the actual global climate system. Based on various assumptions, these models of circulation of the atmosphere and oceans permit the prediction of temperature, precipitation, clouds, winds, and the exchange of energy between the biosphere, hydrosphere and geosphere (Schneider 1989).

GCMs are based on the assumption that climate systems will eventually stabilize, or reach equilibrium. Sensitivity analyses are performed by changing one variable and running the model until it stabilizes. The sensitivity of the model to that variable is determined to show how that variable will influence climate.

A key variable in much climate model sensitivity research is carbon dioxide (CO_2) (IPPC 1990). This gas has increased dramatically in concentration over the last 140 years, 25%, from pre-industrial concentrations, and future increases are expected (IPPC 1990). Carbon dioxide is a good absorber and re-emitter of longwave radiation. Longwave radiation is the only loss of energy to space, and CO_2 impedes this loss. As a result of this trapped radiation, surface temperatures may increase.

It is believed that CO_2 will have the greatest impact in changing the present climate of the boreal region. To determine the climate response to changing CO_2, most models run a $2xCO_2$ climate simulation and subtract a $1xCO_2$ run. The $1xCO_2$ simulation is also compared to observed climate, to validate the suitability of the model.

GCMs are not perfect prediction tools due to the number of assumptions on which they are based. However, they are presently the best means of predicting future climate. For example, one potential problem in using GCM output is the scale that output represents. Model output is in the form of one temperature and precipitation value for an area 10° latitude by 10° longitude. Regional scale influences within such a large area make these values unreliable. A technique to transfer GCM output to regional scale is needed for use in this study.

1.4 Fire Weather Index (FWI)

The CFFDR(FWI) system uses noon measurements of certain climatic variables to produce a daily fire danger rating that estimates the moisture contents of fine fuels (Fine Fuel Moisture Code - FFMC), loosely compacted duff (Duff Moisture Code - DMC), and deep organic soil (Drought Code - DC). The codes relate directly to fuel size, and simulate the moisture conditions of the fuels on the surface. The codes are combined with daily weather measurements of temperature, wind speed - 10 m above surface in an open area, relative humidity, and precipitation to produce two hazard indices: the Initial Spread Index (ISI), and the Build-up Index (BUI). These two indices are combined to produce the FWI. A general description of the FWI and moisture codes follows:

FFMC Fine surface fuels between 0 - 2cm in depth. Values for these range between 0-99, where Low danger is <70; Moderate is 71-87 and High is >88 (in boreal forest of Canada).

DMC Loosely compacted organic material between 2-8cm in depth. Values range from 0-150.[1]

DC Deep, compact organic soil between 8-18cm in depth. Values range from 0-800.[1]

ISI The ISI is computed using FFMC and wind speeds values, and are a good measure of the rate of fire spread. A dependency on wind speed creates a large range in values. Maximum values are common in Alberta during the spring period due to windy conditions.

BUI A numerical rating of the total amount of fuel available for combustion. Combines DMC and DC. Increases over periods of dry weather.

FWI combines all of the above in a numerical rating of fire intensity. Suitable as a general index of fire danger for that particular location.

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[1] approximate maximum values (practical limits) Alexander *et al.* (1982).

DSR Daily Severity Rating. An empirically derived equation describing fire danger and the amount of work needed to contain a fire. The DSR value can be averaged over a fire season to produce a seasonal description (Seasonal Severity Rating - SSR). It is derived using the the FWI value for a particular day.

$$DSR = .0272(FWI)^{1.77} \qquad (1.2)$$

Previous research has used the FWI to study the possibility of increased fire danger due to global warming. Flannigan and Van Wagner (1991) believe that because of its partly empirical basis the FWI is well structured to studies of potential fire effects due to climate change. They assumed a 4°C rise in temperature and calculated the change in the FWI. Monthly anomalies from a 2xCO_2 simulation were superimposed on historical sequences of daily weather for six locations across Canada. Results suggested a 46% increase in the SSR. Flannigan and Van Wagner (1991), however, did not account for the possible changes in the interactions of climatic processes. Instead, they assumed relative humidity (RH) would remain the same and wind speeds would remain constant. They did not determine the effects of changing CO_2 levels or thresholds for these and other important variables.

Beer *et al.* (1988) used the Australian Fire Danger Rating system, which is based on the Canadian FFWI system, to test the effect of potential climate change based on several modifications of the actual daily weather for a 22 year period. They report relative humidity was the most influential climatic parameter in the fire danger index for their fuel type. They state any scenario that assumes relative humidity will not change will likely provide unrealistic estimates of future fire incidence. However, Beer *et al.* (1988) did not determine the critical threshold value in percentage change for relative humidity. The FWI is derived on a partly empirical basis. Generally, a physically based model is presumed to be a more appropriate tool for extrapolating future scenarios. Thus, selected periods of observed fire danger were chosen and used in the Halliwell model for the purpose of testing the sensitivity of various climatic parameters.

Chapter 2

Study Area and Procedures

2.1 Study Area

This research project does not depend on precise microclimate measurements nor is it restricted to one microclimate site. Instead, by utilizing a physically based evaporation model and collecting fuel moisture samples for verification of the model, only a representative boreal site is required. The general evaporation process will be researched and the Halliwell model should be applicable to any area within the boreal forest.

The Lac La Biche Forest area in Alberta, Canada was chosen as the study area for these reasons:

1) It is representative of the boreal forest (Rowe 1977).

2) A large number of Alberta Forest Service (AFS) climate stations are in the study area. With this AFS infrastructure in place, the data needed to test the hypothesis are available.

3) Several Atmospheric Environment Service (AES) stations are also in the area (e.g. Lac La Biche airport and Cold Lake. Climatic records dating to 1953 assist in determining climate variability.

The Lac La Biche Forest lies in the mixedwood region of the boreal forest (Strong and Leggat 1981). The area is characterized by an abundance of needle-leaved conifers in aspen/poplar forest stands. It is in the Cretaceous Upland where relief is not extreme. Preglacial erosion of the soft shale bedrock and subsequent glaciation modified the landscape (Rowe 1977), which is now characterized by rolling morainal deposits on the uplands where trembling aspen (*Populus tremuloides*[2] Michx.), balsam poplar (*Populus balsamifera* L.), and white spruce (*Picea glauca* [Moench.] Voss.) predominate. Black spruce (Picea mariana [Mill.] B.S.P.) dominate glaciolacustrine deposits on the lowlands, and tamarack (*Larix occidentalis* Nutt.) are common in muskeg (Rowe, 1977). These are the typical tree species found in the boreal forests of Alberta. These plant communites differ only by plant species and the composition of the soil and the water table, which varies depending on location.

Temperature has a major influence on the location and maintenance of the boreal forest. A 2°C difference in mean annual temperatures separates the boreal forest region from the grassland region to the south (Rowe 1977). Therefore, not only is a possible 2°C change - a conservative estimate from current GCMs - potentially important to fire danger but it may also result in the migration of tree species. Fire may also be responsible for altering the amount of forest cover, creating larger expanses of 'open' forest.

GCMs estimate that precipitation will increase in

[2] Moss (1983) was authority used for scientific names.

quantity in this location in the spring and fall, and decrease during the summer (Kellogg and Zhao 1988). Precipitation changes will be incorporated into the FWI and Halliwell models to determine the influence of precipitation when combined with warmer temperatures in climate change scenarios.

2.2 Criteria for site selection

To determine the impacts of potential climate change on forest fires in the boreal forest region, two criteria were used for site selection. Initially, a representative forest site was needed.

Within the boreal forest many types of subregions occur. These range from pure black spruce lowland bog ecosystems to mixedwood forests (Strong and Leggat 1981). In selecting a representative stand one criteria was a stand that consisted mainly of softwood, and that had a well developed organic layer.

A site representing large areas of the boreal forest type was preferred for use in both the Halliwell and FWI models. The chosen site is an M-1 Mixedwood stand, as classed by the FDRS (Forestry Canada Fire Danger Group 1992). It consists of 75% softwood and 25% hardwood, with white spruce and trembling aspen forming the major tree species. This stand type is common in the boreal forest especially along its southern limit.

The second criteria was that the site be close to a manned weather station. To satisfy this constraint the site was located 1.1 km from the Beaver Lake Ranger Station, which is at the same elevation as the study area. An automatic weather station, 10 km away at the Lac La Biche airport, gathers information hourly throughout the year.

2.2.1 Site Description:

The site is located on a gently rolling section of forest on the north end of Beaver Lake, 5 km east of Lac La Biche townsite. Site elevation is approximately 562 m. a.s.l. The area is underlain by dark, marine shales of the Lac La Biche Formation. A high clay content characterizes the till and glaciolacustrine materials.

The climate is characterized by warm summers and long, cold winters. Precipitation occurs throughout the year; mean annual precipitation is 460mm, of which 313mm (68%) falls as rain. Mean annual temperature is 1.2°C, ranging from -17.0°C in January to 16.8°C in July (A.E.S. 30 Year Normals 1951-81). There are an average of 65 frost-free days per year (Potter 1965).

Organic materials in the main horizon above the soil (O horizon), are developed mainly from mosses, coarse grasses, needle litter and woody materials. McRae, *et al.* (1979)

recognize three distinct layers in the organic portion of the soil profile; the Litter (L), Fermentation (F), and Humus (H) layers. The L layer is composed of recognizable organic matter; the F layer consists of partially decomposed organic matter and the H layer of decomposed organic matter. The depth of the O horizon within the region ranges from 10 to 25 cm (at the study site: from 11 to 24cm in depth). The O horizon is here referred to as the duff layer and is any layer composed of organic material.

The fire season in the area lasts from mid-April, when human-caused fires in the dried grasses are the ignition agents and primary fuels, to the end of August. The lightning season, which is the primary fire starting agent, extends from late June to early August. Periodically, the fire season extends into September when settlement and recreation (principally hunting) fires cause wildfires.

Fire weather and associated danger can be studied using archived data available from the Alberta Government Forestry Ranger Station at Beaver Lake and the Atmospheric Environment Service (AES) airport station. These data may be used in the FWI program (Van Wagner and Pickett 1985) for an estimation of fire danger.

2.3 Procedures

Field research was conducted from April to August 1993.

During the initial visit to the Lac La Biche area (April 30), a site was located that met the requirements described above.

Fuel moisture samples were gathered during the initial visit for two reasons: 1) To gather samples that were as close to saturation as possible. These data were also used to follow drying trends, especially that of the deeper duff layers, and to test the predictability of both models; and 2) to test the sampling procedure used through the season.

A fuel sampling methodology described by McRae, *et al.* (1979) was employed at the site to gather moisture content samples in an unbiased manner that are representative of the forest as a whole. The triangle has 30m sides. Samples were gathered at 15m intervals along the sides, or at six sample collection sites.

At each sampling site three samples in the organic layer were gathered representing the indices used in the CFFDR(FWI) system. Samples of the surface litter layer 0 - 2 cm in depth; the duff layer, 2 - 8 cm in depth (DMC); and from 8 - 18 cm representing the DC were collected. Samples were dried at 100 °C until a constant weight was reached to determine moisture contents (McRae *et al.* 1979). Periodic measurements throughout the summer show the response to [illegible]ipitation of each layer through the fire season, and the [illegible]ive movement of moisture within the duff layer. Weekly [illegible]sits throughout the season ensured a range of conditions were experienced.

A variety of weather conditions occurred during the summer. The data describes the response of the forest fuels to many different scenarios with changes in moisture content.

Physical measurements of the site were also taken (roughness height, soil profile), primarily for use in the initialization of the Halliwell model. It was hoped that the degree to which the model required a precise site description be minimal. If reasonable evaporation rates were produced it would allow the model to be applied to any similar location in the boreal forest for future modelling.

Sixteen visits were made to the study site during the period April 30 to August 23. Overall, the fire season turned out to be wet. After snow melt (April 10), the duff was near saturation. May was relatively dry and recorded the lowest moisture contents for the season. Fire danger during this period was moderate to high and several large fires occurred (especially in the Cold Lake Air Weapons Range).

In June, precipitation increased in frequency and the temperature was lower than normal. Cool, wet weather continued until early to mid August. Virtually no fire danger existed during this period and there were few fires. This weather pattern also produced the wettest year recorded for parts of the prairies, especially Regina, Saskatoon and Winnipeg). Forty years of fire weather data show the 1993 fire season experienced well below average noon temperatures (15.0 °C compared to the 40-year mean of 16.9 °C); and 400 mm of precipitation. The average fire season precipitation is 315 mm. The resulting Seasonal Severity Rating (SSR) of 0.66, is the lowest experienced during the historical record (1953-1993).

A minor drying trend occurred during the last two weeks of August. Precipitation was minimal and temperatures were seasonal. If a fire had occurred it would have been only a surface fire based on interpreting FWI readings. The fine fuels had dried enough to carry fire, but the lower duff layers were saturated enough to hinder deep burning fires. The fire season ended on August 24 with cool temperatures and 38 mm of rain.

Most of the precipitation in the study period fell in June, July and early August. This is the same time period the Canadian Climate Centre (CCC) GCM estimates a three percent decrease in precipitation under a climate change scenario. This is an important consideration. Generally GCMs suggest an increase in precipitation in $2xCO_2$ climates. However, timing of precipitation during the fire season is the key factor in assessing impacts. In particular, the likelihood of periods of low precipitation is paramount.

2.3 Description of the Fire Weather Index (FWI)

The fire weather index (FWI), which was developed in 1968 is one component of the Canadian Forest Fire Danger Rating System (CFFDRS). The FWI was designed to account for the effects of weather on forest fuels and fires (Van Wagner 1987). It uses daily inputs of local weather, and fuel moisture conditions to compute a relative value of danger. Temperature, relative humidity, wind speed and 24-hour precipitation are measured at noon Local Standard Time (LST) and used to predict the expected peak burning conditions that may occur during the high burning period, ie. 1600h LST; assuming weather conditions do not change. It is a continous accounting system used to calculate a series of numerical ratings representing the three moisture codes.

The three moisture codes are: 1) The Fine Fuel Moisture Code (FFMC), 2) The Duff Moisture Code (DMC) and, 3) The Drought Code (DC).

The FFMC is a numerical rating of the moisture content of litter and other cured fine fuels (examples include spruce needles, twigs, grasses, bark, leaves and small cones). The FFMC was designed to represent fuels on the surface (litter layer) to a depth of 2 cm. These fuels are affected by temperature, humidity, wind and precipitation. Direct calculation of the FFMC is possible when moisture contents of these fuels have been determined (Van Wagner, 1970). Because the FFMC deals with the fine surface fuels its moisture content can change rapidly with the weather conditions.

Surface litter is very important in carrying a fire in its infancy. Fire usually establishes in these fuels before spreading to the larger fuels. The FFMC is an indirect means of indicating the ease of ignition. The FFMC is given more weight in the FWI calculation because it contributes more immediately to fire danger than the DMC and DC.

The Duff Moisture Code (DMC) represents loosely compacted duff and corresponds to the moisture contents of medium sized floor fuels such as fallen small trees and large branches. The DMC layer is in contact with the surface layer, but is estimated by the FWI using temperature, precipitation and relative humidity. Due to its depth, wind does not directly affect drying process in the DMC layer. Rain of less than 1.5 mm in a 24-hour period is not incorporated into the calculation of the DMC. Rainfall of this amount or less is assumed to be intercepted by the tree canopy and the surface litter layer. The DMC layer is affected by the movement of water from both above and below. Water can percolate from above during wet periods and it can gain moisture from below during drier periods when the moisture is migrating upward for evaporation.

The DMC is used to predict the probability of lightning fire starts. Lightning usually strikes a tree and travels down the trunk to the duff layer, thus the moisture content of this layer may determine if a lightning fire will start.

The determination of the DMC from fuel moisture contents can be estimated using equations from Van Wagner (1975). An approximate moisture content may also be calculated after the DMC has been computed by the FWI model.

The Drought Code (DC) is a numerical rating of the average moisture content of the deep, compact organic layers, and used to estimate the moisture content of large sized fuels such as stumps and deadfall on the surface. The DC is an indicator of the long term moisture conditions for an area. It is affected by over-winter precipitation as well as the moisture conditions before winter freeze-up. It can be adjusted at the beginning of the fire season depending on moisture deficiency or abundance over winter.

The fuel layer represented by the DC is in contact with the mineral soil layer below and the DMC layer above. To estimate fire danger, only temperature and precipitation are incorporated into the calculation of the DC. Rainfalls of less than 2.8 mm do not affect the value of the DC as it is intercepted by the forest canopy and the FFMC and DMC layers above it. The drying process of DC layer is relatively slow.

Moisture may move into it from both above and below. Water may move down from above if a large amount of precipitation occurs or from below if the water table is high as occurs in muskeg.

At the study site, most soil water comes from rain. The mineral soil underlying the organic layers is clay, with low moisture contents and slow water movement ability. Throughout the summer the moisture content of the clay layer was consistently lower than that layer representing the DMC. Either the DMC layer had greater moisture holding capacities or the DC layer was only influenced by moisture from above - it did not receive much moisture from the clay. The clay layer acted as a barrier to the upward movement of water and kept the moisture levels of the DC low. Approximate moisture contents of this are may be calculated after the daily DC index has been computed.

2.3.1 Sample Collection

Three samples were taken at each of the six locations on the 30 m equilateral triangle, at depths represented by the FFMC, DMC, and DC, to determine the average moisture content of each layer. They were collected at the same time each visit (1300-1400h), depending on the weather (they were not collected during rain) for consistency of the data. On subsequent visits, samples were taken as close to other collection sites as possible - depending on digging conditions - so a sample represented as similar material as possible. Sample data were averaged for a general description of moisture conditions for the site on that particular day for each layer.

2.3.2 Use of Data

The moisture contents of the three fuel depths were plotted over the fire season and compared to the estimated values from the FWI model over the same time period. This permitted verification of the FWI model and illustrated the response of the fuel to precipitation.

Moisture contents determined by field sampling were comparable to those estimated by the FWI model. Figure 2.1 shows that estimated moisture contents follow the same general pattern produced by the gathered samples. Differences occur in the response of the fuels to precipitation and actual moisture contents. The similarity increased confidence in using historic data to reproduce the FWI for the 1953 - present period. By using historic FWI data periods of extreme danger that have occurred can be identified to understand what was occurring in the fuels, and to use these periods as possible case studies or analogs of future climate change.

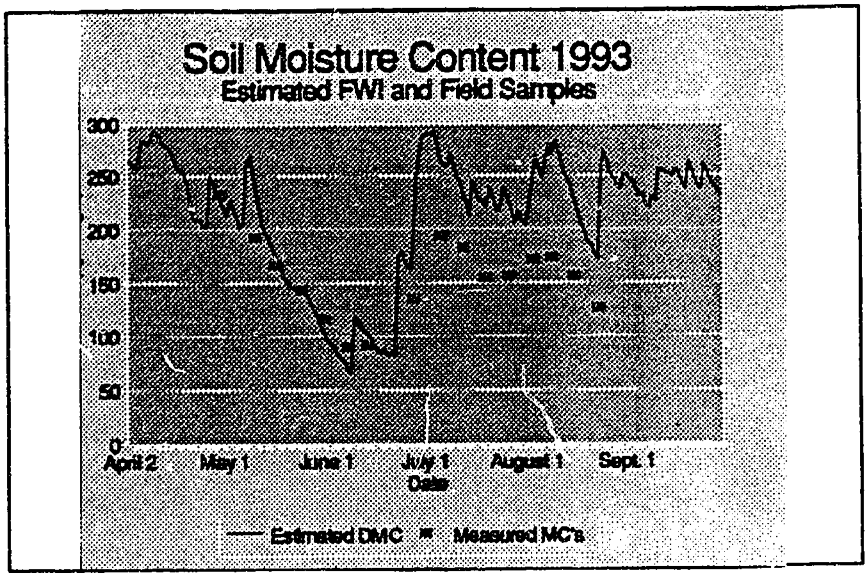


Figure 2.1 Comparison of estimated and measured moisture contents of DMC layer.

The 1993 fire season received substantial precipitation on a regular basis after early June (400 mm of rain fell, 85 mm greater than the long term mean). With high amounts of precipitation, moisture contents returned to early-season values, near saturation, at the deeper levels. Current GCMs predict warmer surface temperatures, and greater amounts of precipitation during certain months. 1993 was almost 2 °C cooler than normal.

Climate change scenarios were run using the changed climatic values to determine if the SSR would increase to levels that would produce a higher fire danger. These scenarios were run through both the FWI and Halliwell models.

2.4 Introduction - Physical Evaporation Model

Fire danger is directly linked to the fuel moisture status (the evaporation that occurs at a specific location). Daily, weekly, and long term weather conditions dictate whether fuels gain or lose moisture. The fire danger may then be estimated by the moisture status of the fuel. Evaporation occurring from the forest floor is critical to the potential fire danger at a particular location.

The Halliwell model is designed to calculate among other things, the evaporation rate for a particular location by determining the rate of vapour transfer occurring at the surface. Initial model conditions, and daily inputs of air temperature, precipitation, humidity, wind speed, and net radiation are used to calculate this rate. The model, which was originally developed for use in a tundra environment, does not consider the evaporation that takes place from the trees, but can show the effects climatic variables have on forest ground fuels. Evapotranspiration from the entire surface (including trees and shrubs), although important, does not alter the fire danger over short periods of time as significantly as the conditions of the dead and downed surface fuels. The moisture content of live or dead needles and leaves is important when fire spread rates are investigated. Because this model was designed for a simple surface - tundra - it is being applied to the forest floor, ie. under the trees and ignores tree effects.

Weather leading to extreme burning conditions tends to occur randomly throughout the fire season, and usually lasts for short periods of time. These conditions are responsible for most fire damage. Fire occurrence is a short-term phenomenon, and is primarily a function of the moisture content of the finest fuels. Analyzing fire weather data (1953-present) along with fire losses allows these high danger periods to be identified. The FWI model was used to identify these periods for use in the Halliwell model for an in-depth analysis of evaporation rates and soil moisture conditions.

The model calculates evaporation rates and soil moisture conditions, and therefore, should be applicable to an examination involving fire danger. Changes to single, or combinations of weather variables, can be performed to test model sensitivity and reflect climate change conditions. Output can then be compared to collected moisture samples and conditions estimated by the FWI model.

Numerous techniques have been used to manipulate climatic data in models that investigate the impacts of global warming. One technique is to use direct output from GCMs as monthly averages, while another uses historical sequences of daily weather and modify the climatic variables by the amount GCMs have determined. This research uses the latter; it is an offsetting technique which assumes the distribution of values of weather variables about their means is not affected by climate change (Robock *et al.* 1993). Such an assumption is an important consideration. Currently, the study of climate variability is still being developed. Historical sequences of daily weather were used, and offset by the amount estimated by a chosen GCM scenario. The increases (or decreases) were applied to all daily temperatures and precipitation values within a sequence. This technique, and the reasonablness of this assumption has been widely accepted (IPPC 1991).

The physical evaporation model (Halliwell 1989) attempts to partition net solar radiation available at the ground surface into atmospheric and sub-surface components. Net solar radiation for the purpose of the Halliwell model is defined as the sum of the three fluxes (QH, QE, and Qg) as in equation (1.1). The partitioning of the available energy varies depending on daily weather conditions. The division of energy between thermal heating of the atmosphere, evaporation of available moisture, and thermal heating of the ground, will produce different rates of evaporation and influence the fire danger at a specific location. The model allows the examination of the resulting effects on the partitioning of energy.

The Halliwell model is largely physically based, once it is initialized it should be applicable to other physically similar environments. It was developed and tested near Churchill, Manitoba. The physical environment there is strongly influenced by permafrost. The specific site was unforested, and the surface was dominated by organic soil (peat). The vegetation layer was restricted to small shrubs and surface water was common. The physical characteristics of the boreal forest study site used in this trial are different, therefore some modification of the evaporation model is required. This entailed initializing the model for use in a forest environment.

One component of this research is to determine whether the model is applicable in a forest ecosystem. If the model is accepted, it may then be used for sensitivity tests relating to possible climate change scenarios.

2.4.1 **Model Description**

A complete description of the model can be found in Halliwell (1989). In brief, model uses daily inputs of net radiation, temperature, vapour pressure, wind speed, and daily precipitation. These can be modified to test model sensitivity and for fine tuning.

Model output includes surface temperature and soil temperature profile, surface and soil moisture conditions, and the partitioning values of the three energy fluxes (QH, QE, Qg).

In open environments, wind has an important influence on evaporation rates. In forested locations wind effects decrease as the distance increases from the forest edge. Wind speeds can drop to 0 m/s as fetch increases. (Distances of 400 m from the forest edge have been found to effectively eliminate the impact of the wind profile (Monteith 1975, Vol.1)). Tree density and species composition can influence this effective distance.

The wind speed profile used in the development of the model was also utilized in this research. The log scale description calculating the wind speed profile, used in the tundra environment was not modified. This profile is important in calculating the resistance factor controlling vapour transfer at the surface, and ultimately the evaporation rate. In open environments, due to reduced friction from the surface, wind speed increases at a log rate with height (Oke 1987). Directly above the surface, a laminar flow layer exists in which there is no wind. Energy is transported via conduction. From the top of this layer to eg. 10 m in height, wind speed increases at a logarithmic rate. Forest influences complicate these calculations (Branson 1989).

The forest contains many areas with different microclimates which create unique wind speed profiles. Developing an appropriate profile would be beyond the capabilities of this study. Branson (1989), also used the logarithmic profile as an aerodynamic parameter to describe the effects of wind on evaporation in a mixed forest in Ontario. He reasoned the influence of canopy geometry on aerodynamic parameters was difficult to evaluate for a single site, since profile parameters and canopy geometry are variable.

The energy exchange that occurs at the surface was described in equation (1.1). The partitioning of these fluxes determines the equilibrium surface temperature (T_s). T_s is used to produce the soil temperature profile and in calculating the evaporation rate. The evaporative surface temperature is derived from this temperature.

The turbulent fluxes (QH and QE) are calculated using the aerodynamic method (Oke 1987), with an aerodynamic resistance determined from the wind speed and surface roughness (Halliwell 1989).

The determination of T_s can be achieved using equations that calculate Q*, QH, QE, and Qg (Halliwell 1989). These equations were chosen because they can be set up with the only unknown variable being T_s.

Equation (1.1) can be rewritten as:

$$Q^{*} - QH - QE - Qg = 0 \qquad (2.1)$$

The three fluxes (including Q^{*}) are influenced, and can be solved by knowing T_s. Separate solutions for each flux enable the user to isolate T_s as the only unknown. For any given T_s all four fluxes can be calculated.

Q* or net radiation can be solved using the following equation:

$$Q^* = K\downarrow - K\uparrow + E(L\downarrow - \sigma Ts^4) \qquad (2.2)$$

where E = surface emissivity

K = shortwave radiation flux (↑ or ↓)

L = longwave radiation flux

σTs^4 is from the Stefan-Boltzmann law ($E = E\sigma Ts^4$) (Oke 1987).

As a first approximation, Q^* can be taken to equal $K\downarrow$, as the Halliwell model does not calculate the loss to space ($K\uparrow$), nor does it consider incoming longwave radiation ($L\downarrow$)

The Halliwell model was developed to place a greater importance on the determination of QE. In general, QE is controlled by the surface resistance (r_s), the difficulty or ease at which water vapour moves across the surface layer, and is examined and calculated in great detail in this model. This will hopefully produce better estimates of QE.

2.4.2 Model Initialization

A number of requirements are needed to initialize the evaporation model.

1) Initial surface temperature - estimated from air temperature.
2) Height of surface roughness elements - estimated from vegetation height.

3) Soil moisture conditions - determined from sampling. Includes soil temperature profile, by layers, by depths, and by thermal properties.
4) Measurement heights - 1.5m for temperature and humidity, and 20m for wind speed.
5) Crown closure - on site measurements and forest cover maps.
7) Site location - latitude and longitude.
8) Parameters for surface vapour resistance cycling.

The model is run with daily inputs of temperature, vapour pressure, wind speed, precipitation, and net radiation. Temperature, wind speed, precipitation, and vapour pressure are all determined from measurements taken at the Beaver Lake district office. The microclimate station is in a relatively small opening close to the forest boundary and it simulates a large opening within a forest stand.

Daily net radiation (under the canopy) was not measured directly at the site but was calculated using collected data from other sources (D. Chesterman (University of Alberta - Geograpy) personal communication 1993). The forested site has a canopy coverage of roughly 60% with an average tree height of 23.5 m. The amount of incoming radiation at the top of the canopy will differ greatly from that at the surface and affect the resulting evaporation rate.

Cloud cover (in tenths) data from A.F.S. noon weather observations were used to compare net radiation and sky conditions, and to synthesize time series of net radiation when historic time series of cloud data was not available.

The calculations to determine net radiation reaching the forest floor used data provided by D. Chesterman (personal communication 1993).

Photosynthetically Active Radiation (PAR) data were collected under the forest canopy. PAR incorporates radiation in the 400 - 700 nm wavelength (visible light spectrum), which is transmitted by the vegetation. Data are collected at a number of locations consiting of differing stand ages, densities, and species. PAR data were taken from as similar a stand as the one used in this study. The particular stand was a mature site containing aspen and white spruce. PAR represents the amount of energy transmitted by vegetation and is collected at 1.5 m height. The PAR value did not need to be precise because PAR changes between microsites.

PAR makes up approximately 36% of the total energy incident on the atmosphere (Ross *et al.* 1986). The spectral distribution of light energy incident on the atmosphere is shown in Table 2.1: (It should be noted that Wm^{-2} adds to 1350.16, based on 1965 values. 1368 Wm^{-2} is now the accepted figure for the solar constant. The percentage of energy at each wavelength should not change.)

Table 2.1 The partitioning of energy by wavelength.

Wavelength(nm)	% Energy	Wm^{-2}
below 200	0.1	1.36
200-300	3.0	40.8
300-400	8.9	121
400-700	36	490
700-1000	24	326
above 1000	28	381

Scattering, reflection and absorbtion of energy with wavelengths below 200 nm and above 1000 nm occurs before penetration to the earth's surface. Wavelengths between 200 nm and 400 nm also decrease radiation intensity by 9%. These losses can be omitted from the available energy at the surface and thus, the contribution of PAR increases. PAR makes up roughly 50% of the total solar flux available to the surface (Lee, R. 1978). To verify this assumption, data were collected over a three-day period (April 5 to 8, 1994) to determine the amount of PAR in relation to solar radiation. Data were collected by rooftop measurements, at the University of Alberta. On clear days PAR made up 38% of net radiation, on cloudy days it was 42%. For the purpose of this research, PAR is taken to be 40% of net radiation, and solar radiation is equal to net radiation from the explanation given with Equation (2.2).

Daily PAR data were collected for the fire season at the other site. The similarity between sites, their close geographical proximity, and because only an approximation for the evaporation model is sought, data incorporated in the Halliwell model were an estimate of net radiation under the canopy.

PAR data were converted to units (Wm^{-2}) for use in the evaporation model from micro moles/s^{-1}. Hourly readings of PAR were summed into daily totals.

2.4.3 Canopy Influence

The forest canopy influences the quantity and quality of incident solar radiation eventually reaching the forest floor. The quantity and quality of solar radiation within the canopy is a function of the density and structure of the forest system, solar elevation, and sky conditions. The research site consists primarily of white spruce and is bordered by aspen on one side. The influence of an understory, <3m in height, is minimal as there are few immature spruce or aspen.

White spruce 'tend' to produce an inverted cone crown shape. Crowns cover less surface area than pine or deciduous stands in full leafout, allowing a higher proportion of direct-beam radiation to reach the forest floor (Ross 1986). The study site is relatively open (~60% crown closure), thus the light regime is influenced more by solar elevation and cloud cover, than by canopy closure.

2.4.4 Cloud Cover

Cloud cover data were gathered from Alberta Forest Service afternoon weather reports. Cloud cover was categorized from clear (0) to overcast (10) (in tenths).

Data were broken down from values ranging from 0 to 10 and placed in four categories (Table 2.2).

Table 2.2 The cloud cover categorization used as gathered from the A.F.S. (in tenths).

Cloud Cover	Category
0	clear
2.5	scattered
6	broken
9	overcast

Cloud cover can have a large influence on the amount of direct solar radiation received by a site (as much as 40% compared to a clear sky) over the course of a day. Cloud cover can also influence PAR. The data shows that the amount of PAR can change from 8.64 $MJm^{-2}day^{-1}$ on a clear day, to 3 $MJm^{-2}day^{-1}$ the next day when cloud cover is 9 tenths. Changes in same day cloud coverage were not included in the categorization.

Between 40 and 50% of the total radiation at a site consists of PAR. Clouds can reduce the total amount of radiation depending on the amount and type of cloud cover.

Forest canopies lessen the amount of direct radiation that reaches the forest floor. Cloud data were used in conjunction with PAR data for simulations of the 1993 fire season. Increases and decreases in PAR values were consistent with the cloud data.

Simulations of years, other than 1993, required synthesizing a PAR time series. Ross *et al.* (1986) found the PAR values followed a distinct pattern over the course of a fire season. In early spring, PAR reaches its highest values before aspen trees have fully leafed out because all solar radiation is able to penetrate directly to the forest floor. This pattern also exists in coniferous forests, but to a lesser amount than in deciduous stands. PAR values then decrease over the summer, and increase slightly in the fall when leaves drop from aspen trees.

The PAR data used in this study follows the same pattern. To synthesize a time series, monthly averages of PAR were calculated dependent on cloud cover and the amount of incoming extra-terrestrial (E-T) radiation for the site. Monthly averages were determined using standard astronomical calculations, on location (lat/long), date and time (solar).

For each category of cloud cover, a range of recorded PAR values appeared. Data were consistent in that clear days had a range (and average) that was greater (in Wm^{-2}), than days with more cloud cover. This pattern consistently described days with 0, 2.5, 6, and 9 /tenths cloud cover.

The PAR averages were calculated for each month of the season and combined with historic cloud cover data. All days with similar cloud cover were assigned an average PAR value taken from the 1993 data. Initial runs of the model using a synthetic PAR time series show this as an acceptable technique. Table 2.3 shows the complete list of initialization variables used in the Halliwell model.

Table 2.3 The initialization variables from the Halliwell model.

Variable		Value
Time step		86,400 seconds (day)
Ht. of anemometer		20m
Ht. of air temp.		1.5m
Surface roughness length(zo)		1.3m (Zo = .13h)
Initial surface vapour resistance		275 (s/m)
Ratio vapour/thermal resistance		0.0
Max. surface vapour resistance		1000 s/m
Initial water content		0-2cm 100% 0.875 by volume, 2-8cm 232.5%, 0.87 8-20cm 177%
Max. water content		170% (surface) .875
3 Coefficients for resistance cycling		C1: 300,000s/m^2 C2: 0.18m C3: 1.5m
No. soil layers		3
Name of soil		0.0 - .24m Organic (duff), 0.25+m Gleysolic clay
Depth of base of soil layer		0.24m Organic, 0.50+m clay
Soil solid fraction		.650
Heat capacity/volume		.6cal/g C°
Fraction water content		0.13
Thermal conductivity	Organic wet	.85 (W/mC°)
	dry	.20 (W/mC°)
	Clay wet	2.90 (W/mC°)
	dry	2.30 (W/mC°)

CHAPTER 3

Scenario Generation

3.1 Introduction

Climate change may adversely affect our environment. Climate models, particularly GCMs, indicate a rise in mean global surface temperatures and the forest industry is particularly interested in how such a change will affect the forests. Tree species migration, growth rates, insect and fire damage may all be influenced by a change in average surface temperatures and precipitation patterns. One objective in this thesis is to generate the most as realistic scenarios as possible to study the potential impact of climate change on the forests, and in particular, fire danger.

Present GCMs include: (1) realistic geography, (2) interactive clouds, (3) terrestrial vegetation and hydrology, (4) polar sea ice and, (5) to a greater or lesser degree, some interaction with the ocean surface. Currently they are the best means we have of simulating the climate system.

To create a scenario for impact assessment requires a knowledge of climate change on the regional scale. The resolution of current GCMs is large; grid sizes of 7° latitude by 10° longitude are common, though newer models are producing smaller grids. Physical values for factors such as temperature and precipitation are averaged over large areas for a grid cell and are given as one value, usually as monthly anomalies (the difference between the $2xCO_2$ simulation minus the $1xCO_2$ simulation).

A regional climate is strongly influenced by the time-averaged level of net radiant energy at the surface. Abrupt changes in surface features occur within a GCM grid. These create large differences in temperature and precipitation over small areas, smaller than the present grid system GCMs can realistically develop.

The boreal forest in Canada covers an area from N.E. British Columbia to Newfoundland and as far north as Yellowknife. GCM output should be applicable at this scale, but regional influences may not be accounted for in the models. Local influences create zones where a single output value is usable but does not represent the entire cell.

A technique is sought that will produce a scenario that is as realistic as possible, given present model limitations. The technique must include a sound knowledge of the present day climate, i.e. for the Lac La Biche region; include all present day variability; and physically represent processes occurring now and which may occur in the future.

Current GCMs indicate a rise in mean surface temperatures and increases in precipitation (certain areas such as the continental interior may experience a decrease in precipitation during summer months, Kellogg and Zhao (1988)), including possible changes in the timing of the precipitation. Timing of precipitation during the fire season is very important to fire danger. As well, greater evaporation with an increase in average temperatures may lead to decreases in soil moisture, increasing fire danger. All these events are possible. Therefore, creating a regional scenario that is an accurate representation of future climate is problematic.

Many studies are involved in scenario developments on a regional scale. They attempt to use physically as well as statistically consistent properties to describe the relevant parameters in the modelled simulation. Precipitation, especially the timing of the events, remains an uncertainty.

Some climate change scenarios alter only temperature and precipitation when investigating fire danger (Flannigan and Van Wagner 1990, Balling *et al.* 1992), and maintain the statistical relationships consistent with present time series. Other investigations have altered relative humidity, Beers *et al.* (1988), whereas some like Fried and Torn (1990) have altered all four parameters; temperature, precipitation, wind speed, and humidity. The justification these studies use for selecting different parameters to change, is in part due to the reliability researchers hold in different GCMs. Most GCMs only agree on the sign of change for temperature and precipitation. Relative humidity and wind speed can have different signs depending on the model used.

Fire danger is influenced by temperature and precipitation. One mean temperature and precipitation value produced by a GCM may not be realistic at present grid size. Simply adding a $2xCO_2$ - $1xCO_2$ simulation and imposing the difference on a current time series may not produce scenarios with appropriate spatial and temporal details without corrections for the initial models' deficiencies.

There are four common techniques used to create climate change scenarios; using data from the instrumental record; the use of paleoclimatic information; synthetically generated time series; and scenarios derived from climate models. Each method has inherent advantages and disadvantages, but all have been used in studies dealing with impacts on a regional basis (Easterling *et al.* 1992, Wigley *et al.* 1990, Robock *et al.* 1993, Smith and Tirpak 1989, Karl *et al.* 1990, Woo 1992).

Using data from the instrumental record is also known as the analog method. Accumulated climate data are used to simulate the future under a changed climate. Analog methods can include the use of specific years or certain periods that experienced a climate either warmer or colder than the present. Easterling *et al.* (1992) used climate data from the 1930's as an analog for future climate warming for the

American midwest.

Paleoclimatic data utilizes proxy data to generate climate change scenarios. Past evidence of colder or warmer periods are used to generate scenarios. There are certain obstacles with this technique. Forcings that created either warmer or colder periods in the past may not be the same as those which may occur in the future. The data may thus be biased and the methods used for analyzing it inaccurate. Built in systematic biases may be present when dealing with the geologic record. These reasons may make the data unusable.

Synthetically generated time series are a well-used method of scenario generation that are applicable when the important parameters relevant to a study are known, and when the goal is to create statistically similar time series based on the current climate. This technique has the advantage of incorporating the variability of the present day climate into the generated time series.

The use of climate model output are now a popular means of creating climate change scenarios. GCM output is used by imposing an amount of change onto a present day time series. One advantage is that physically, as well as statistically consistent properties are maintained. Future forcings are incorporated and variability is maintained by the current time series.

Climate variability in the future may not mirror climate variability of today. Presently, it is unknown how daily variability may change. Most studies use present day time series and impose GCM output. This may not be what will occur, but it is the only technique now available that is scientifically acceptable and is not based on speculation.

Realistic scenarios can only be created by understanding the processes influencing the selected study area. A knowledge of local weather patterns and a statistical understanding of the climate are crucial.

The climate change scenario in this thesis is based on statistically and physically consistent properties that allow the timing of climatic events to change. Different aspects of various studies mentioned are incorporated to create a scenario to test the sensitivity of the CFFDR(FWI) system and that of the Halliwell model. It would be unwise to create a scenario where all parameters are altered because it would not be consistent with present day climatic time series, and it would not be physically based.

In this thesis the timing of precipitation events are adjusted to determine the influence on fire danger. Robock *et al.* (1993) used the same technique based on an understanding of the modes of natural interannual variation for specific regions, to create regional scenarios. It is assumed the physics governing a GCM produced climate are the same as at present, but the physics is specified by the climate system, not the computer model. For example, the start of the rainy season may occur consistently within a two week period every year and is verifiable with climate records. A GCM produced climate will show one value for precipitation for the month. Although the statistics may be consistent in the computer model, nature specifies the regularity of the timing.

3.2 Techniques Used

Glantz (1989) described steps needed to create a regional climate change scenario and this method is used here. His methods can be followed when the study of regional impacts due to climate change are undertaken. Robock *et al.* (1993) proposed the following:

1. Select type of climate change, e.g. greenhouse warming.
2. Select system that affects humans, e.g. the forest ecosystem.
3. Select technique for determining impacts, e.g. FWI and evaporation model.
4. Determine the necessary climatic parameters for use in impact analysis based on 1, 2 and 3. e.g. temperature, relative humidity, wind speed and precipitation.
5. Choose technique to generate climate scenarios.
6. Generate scenarios.
7. Determine the range of impacts using techniques selected

in 3 and scenarios in 6. Conduct sensitivity analyses using technique selected in 3 to estimate uncertainties and error propagation and to identify most sensitive components.

8. Repeat 1-7 for all possible combinations of 1,2,3, and 5.
9. Determine all human technological, sociological, economic, political, and military responses to each impact from above, singly and in all combinations.
10. Assign probabilities to each choice and result above, and determine the net human impact.

This thesis follows steps 1-7. Steps 8-10 would require a much larger study. The goal is to create a scenario that is statistically consistent and physically based, and which allows the timing of precipitation events to be altered.

3.3 Choice of General Circulation Model

The GCM used was one developed at the Canadian Climate Centre by Boer *et al.* (1984) CCC GCMI, and revised by Boer *et al.* (1992) CCC GCMII. This model was chosen because it is first, one of six world class models in existence, and one of only three 'second generation' models, and secondly, only a range of potential change is needed for use in fire weather scenarios. CCC GCMII output is consistent with other world c'ass GCMs.

As in other models, there is good agreement on large-scale changes, especially in the sign of change for temperature. Present day GCMs, although advancing in methods used for numerical solutions and parameterizations, still exhibit an incomplete understanding of some processes: sources and sinks of greenhouse gases, clouds, oceans (which influence the rates of change), polar ice sheets, and components of the hydrological cycle (Climate Change Digest CCD91-01).

Results of the CCC GCMII simulated equilibrium climate response to a doubling of CO_2 are as follows:

Temperature: An increase of 3.5°C for annual average surface temperature. This compares to a 4.2°C rise from the CCC GCMI model.

Precipitation: An increase of 4% globally. Some regions such as the continental interior may experience a decrease. This value is lower than that from the GCMI.

Evaporation: Evaporation rates are expected to increase by 4%. The continental interior may experience a decrease as with precipitation.

Soil Moisture: A decrease in soil moisture (6.6%) is expected in middle latitudes and be greatest in summer.

Cloud Cover: A decrease of 2.2% globally is expected.

GCMII uses an interactive cloud scheme compared to prescribed clouds in GCMI (Boer *et al.* 1992).

Output from the CCC GCMII can be used in both the FWI and physical evaporation models. Monthly changes determined by the GCM are superimposed on existing time series to create scenarios of possible future climate change.

3.3.1 Choice of Regional Scenario

To create a regional scenario for use in impact studies, physically and statistically consistent data are created from historic time series with the amount of change from the CCC GCMII 2xCO_2 - 1xCO_2 simulation imposed on them. 21 years chosen from the period 1953 - 93 (based on a complete data set), were run with the climate data altered by the GCM output. Specifically the changes estimated by the CCC GCMII in a doubled CO_2 scenario are shown in Table 3.1.

Table 3.1 Estimated changes in temperature and precipitation values for the Lac La Biche Region.

Temperature:	April-May	- increased 4.0°C
	June-August	- increased 3.9°C
	September	- increased 3.0°C
Precipitation:	April-May	- increased 32%(or .4mm/day)
	June-Aug.	- decreased 3%(or.08mm/day)
	September	- increased 30%(or .4mm/day)

* Interpolated from CCC GCMII Maps (Boer 1992).

The increases in precipitation appear large, but generally, little precipitation falls during April, May, and September in Lac La Biche (Figure 3.1). Most precipitation falls in the June-August period, when a decrease is suggested. As in most studies using fire models and GCM results, temperature and precipitation are the variables most easily altered, based on model comparisons. Potential changes in wind speed and relative humidity pose a more challenging problem to researchers.

There are two theories regarding changes to wind speed. Firstly, a smaller pole to equator temperature gradient is predicted with climate change (greater amounts of warming

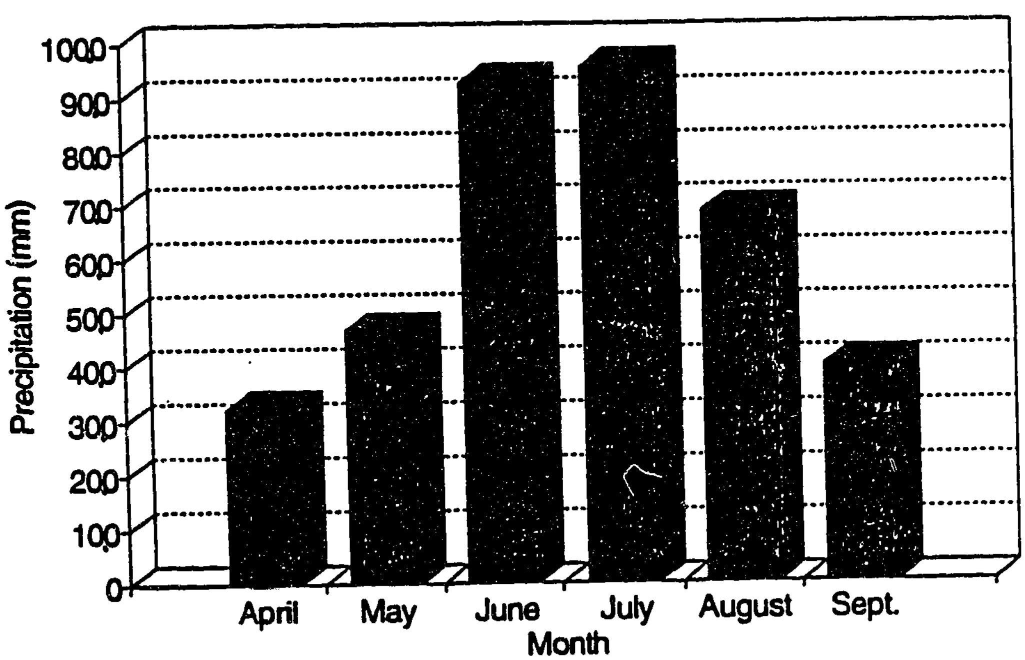


Figure 3.1 Monthly precipitation for the Lac La Biche region based on a 10 year data set.

are expected in the polar regions). This pattern may produce less energy in the atmosphere and therefore less air movement. Alternatively, greater evaporation from increased surface temperatures may result in a greater number of convective storms and increase local winds. With these two contrasting theories, most studies do not alter historic wind speeds. Sensitivity tests using both models were still performed to determine the importance of windspeed on simulated fire danger. These were run with increased wind speeds and also with no changes to existing time series. Cumulative wind speed graphs were produced (Figure 3.2). These show the maximum and minimum wind passage for the study period, as well as a normal season. The amount of change from one year to another was minimal and therefore the influence of cumulative wind speed on fire danger is believed to be minor.

The impact of climate change on relative humidity has received much attention. Fried and Torn (1990) used two methods to test the effects of climate change on relative humidity in their fire model. First, they scaled the change in absolute humidity from GCM output. They also took the change in relative humidity directly from a GCM and applied it to a historical sequence of climate data. Both yielded results that were nearly identical and show no significant change in humidity due to climate change.

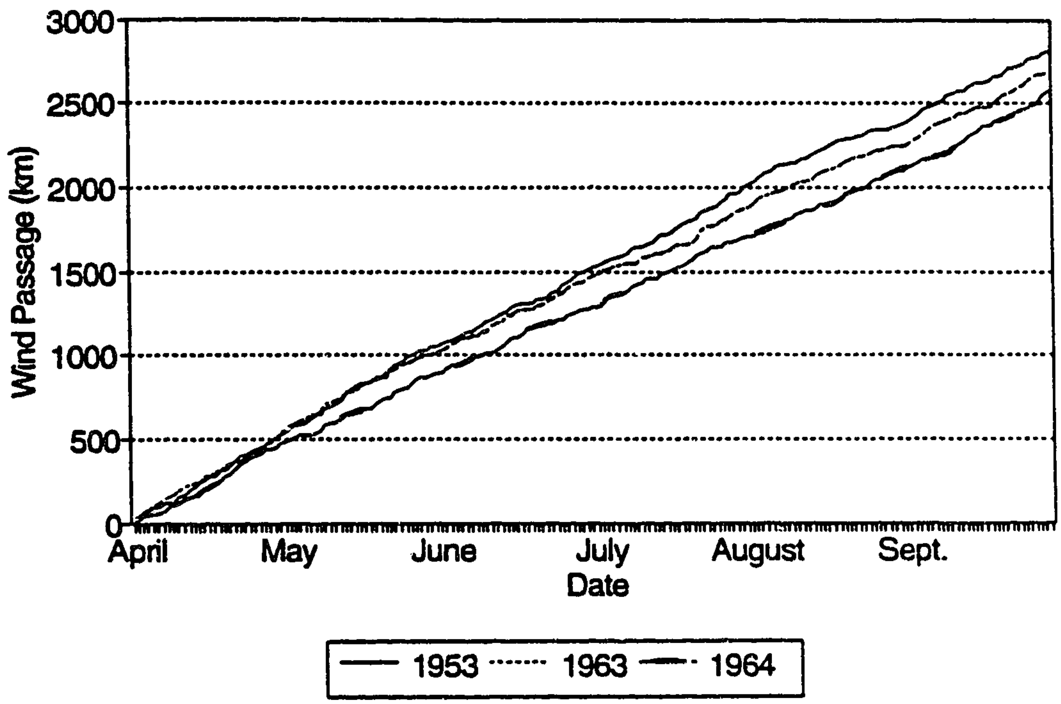


Figure 3.2 Cumulative wind passage for a high, normal, and low wind speed year.

Simard and Main (1987), simply used the results of one GCM producing a 1% decrease in relative humidity at 35°N and imposed this value onto daily time series.

Flannigan and Van Wagner (1990) believe when a constant dew point is assumed, the effects are important in the FWI model because the change in relative humidity is downward only. However, holding relative humidity constant may be a more accurate representation in a warmer climate. Increased precipitation, temperatures, and evapotranspiration will allow the relative humidity to remain relatively unchanged. They agree with Rind (1986) who found relative humidity tends to remain constant when simulating either warm and cold climates using the GISS GCM. Rind states that the invariance of relative humidity is now a standard assumption in radiative-convective models.

Beers *et al.* (1988) used a scenario developed by Pittock and Nix (1986). They imposed a 20% reduction in relative humidity values to historic time series. Their calculations found relative humidity to be the most important parameter to Australian fire danger. A 20% reduction in relative humidity appears as a large change. Average relative humidities in their study area are 50%. Lac La Biche data show an average relative humidity of 56%. A 20% reduction would reduce average relative humidities from 50 to 40% A change this large for the Lac La Biche region would also make relative humidity the most important parameter.

Relative humidity was altered in this study for model sensitivity purposes. Both models were run with small changes (2%), and also with no changes to relative humidity.

3.3.2 Timing Change of Climate Variables

The timing of certain events, especially precipitation, can have a profound impact on fire danger. Fire danger is greatly influenced by short periods of extreme fire weather. These periods almost always occur in combination with extended periods of no, or very little, precipitation (<1.5

mm). A study of seasonal precipitation patterns of the Lac La Biche region reveals some noticeable patterns.

The majority of fire seasons begin with extended periods of dry weather. Little precipitation falls from the average date of snowmelt, [Median, April 17; earliest, March 29; latest, May 15 (Potter 1965)], until the first week of June. This is one reason the spring season contributes strongly to the seasonal burn total. The rainy season routinely begins during a two week period near the beginning of June. Figure 3.3 shows the general cumulative precipitation pattern of the Lac La Biche region. The season begins with little precipitation in the months of April and May. Greater frequency of events and amounts occur during the June-August period, generally followed by a dry September.

Robock *et al.* (1993) found a similar pattern in an impact analysis of the Sahel desert and the impact of rainfall timing on agriculture. Robock *et al.* (1993) create a scenario maintaining the statistical and physical consistency shown by the climatic time series. This technique allows the starting date of the rainy season to vary, thus it may be applied to study potential impacts on fire seasons in Lac La Biche. If rain begins 10 days later in the year, the number of extreme danger days may increase.

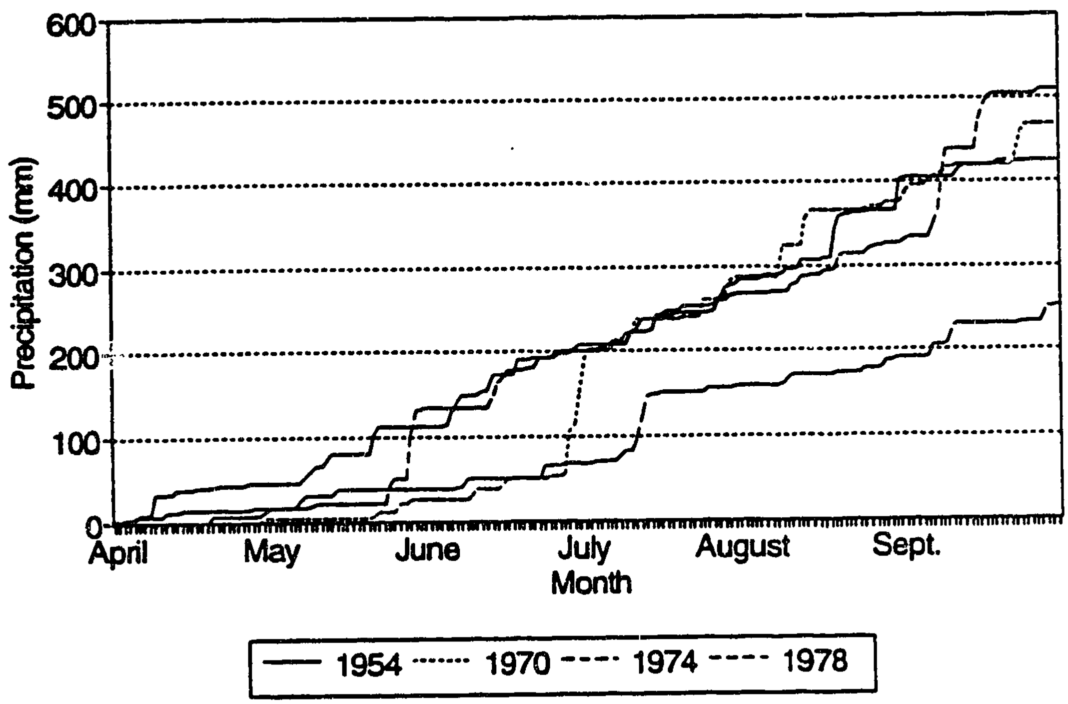


Figure 3.3 Cumulative precipitation patterns for Lac La Biche. These seasons show the range of the onset of the rainy season.

In spring, the amount of dried grasses and other small fire carrying fuels in the forests is high. These fuels are usually extremely dry and carry fires quickly if accompanied by moderate winds. Such fires do not usually burn deep into the organic layer but are able to climb into the trees to produce crown fires. When late spring rains arrive, green-up occurs; dead, dry grass is replaced by green grass, and the shrub layer greens-up. The potential of fires to run quickly through forest floors and climb up into the crowns is reduced. Greater numbers of hectares are burned in the spring and late summer when the grasses and shrubs begin to dry.

Extreme fire weather in late July, when the potential for lightning still exists, also contributes to higher danger and the potential for more and larger fires.

Robock *et al.* (1993) assume the climate system will continue to vary in the future as it does today, and that by using interannual differences, the possible scenarios will not conflict with the known physics. Both models can be set-up to change the timing of climatic variables that may occur in the future and which may have a large impact on a regional scale.

In this thesis, existing time series are used and altered by GCM output. Following Robock *et al.* (1993), the timing of precipitation is also changed. Both models can then run to study their sensitivity to these changes. Precipitation events may be moved forward or backward with amounts determined by the ratio of change predicted by the GCM.

The timing of certain climatic variables, especially precipitation, is still unknown. But the impacts of these changes are important. If temperature change is not significant, but precipitation timing changes, it may affect fire danger. This technique of altering the timing of rainfall is incorporated as a potential change. It may be considered weather forecasting, instead of climate change prediction, but because timing is so important to potential fire danger, it has been included.

Generated scenarios are subject to many limitations, therefore the assigning of probabilities should be avoided. There are uncertainties in the GCM, FWI, the Halliwell model, and the development and use of a regional scenario. Results of this and other studies in this area should be regarded as sensitivity tests of the models themselves, not forecasts.

CHAPTER 4

4.1 FWI Simulation

In this chapter the FWI model is used to provide a general description of the types of fire seasons that have occurred in the Lac La Biche forest. Model sensitivity to changes in individual variables are performed along with seasonal simulations. Climate change simulations are also run.

The FWI model was used to analyze fire seasons with varied fire dangers using historic data. These seasons are then run in the Halliwell model to discover and quantify climatological influences. Initially, though, selected historic fire weather data from the period 1953 - 93, was run in the FWI model. Output was analyzed along with annual fire data of the Lac La Biche Forest to gain an understanding of the fire environment. Selected fire seasons, based on complete fire weather data, will be analyzed and run with climate change scenarios to determine changes in soil moisture and fire season characteristics. Model input and output were described in Section 1.4.

4.1.1 Data

Fire weather data were collected from both the Alberta

Forest Service and Atmospheric Environment Service records for the period 1953 - 1993. Fuel moisture samples collected in 1993 were used to verify FWI model output using fire weather information. The samples, especially those of the DMC, displayed a strong correlation with estimated values of fuel moisture indices. Correlation values comparing actual FFMC and DMC samples versus predicted (FWI model) values were 0.4301 and 0.6869 respectively, at a significance level of .95. FFMC values varied site to site depending on exposure, and fluctuated on a daily basis. Collected moisture contents were consistently higher than those predicted by the FWI model. After rainfall events differences were exposed. More dramatic fluctuations existed in collected moisture content samples. The FWI model decreased its values more slowly than those of the actual samples. Moisture penetrated the top duff layer (to 8cm) faster at the study site than that predicted by the FWI model (See Figure 2.1).

4.2 Fire Weather

Twenty seasons (April - September) of fire weather data (plus 1993) was collected and studied in the FWI model from the 1953 - 1993 period. The availability of data negated the use of some years in the data period; some years had missing records, whereas in other years the moving of a weather station resulted in periods of no data. Of the selected years, 6 experienced fire losses greater than the calculated normal; 8 experienced seasons with practically no danger (including 1993); and 6 years were rated as normal.

Table 4.1 shows climatic averages of the chosen fire seasons and their associated SSR. (Values are averaged from April 1 - September 30). The values in the table represent 12 LST observations.

4.3 Fire Danger

A simple technique was needed to classify fire seasons. Previous studies found temperature and precipitation to be the most important climatic variables affecting a seasons fire danger. The seasons were therefore classified as either; warm, normal, or cool, and dry, normal, or wet according to their temperature and precipitation characteristics (Table 4.2). These were categorized according to their means and standard deviations. If a season was greater or smaller than one standard deviation from the mean, a change in the seasons classification occurred.

Nine categories of fire seasons occur with this scheme. To determine the impact temperature and precipitation have on fire danger initial comparisons were made comparing season type to the number of hectares burned (Table 4.3).

Table 4.1 Selected seasons fire weather characteristics based on seasonal means.

Year	Temp(°C)	RH(%)	Wind(kmh)	Prec.(mm)	SSR
1953	17.24	58.99	14.05	259.5	2.09
1957	17.65	57.14	10.0	204.3	2.43
1958	18.40	54.71	13.16	203.5	4.39
1961	18.28	55.73	15.57	265.1	4.40
1962	17.09	59.86	14.33	440.3	1.43
1963	18.86	55.96	14.6	282.5	2.51
1964	17.60	57.17	15.18	316.8	3.33
1967	18.15	54.14	13.72	263.3	4.27
1968	16.98	55.51	15.04	297.2	3.43
1969	17.64	58.32	13.87	425.8	1.81
1970	17.80	59.33	15.07	469.3	2.95
1973	15.96	67.37	11.42	389.8	.97
1975	14.37	62.56	11.13	465.0	.76
1977	16.12	58.88	7.6	358.7	.69
1984	15.43	55.79	11.21	348.4	1.52
1988	16.35	55.03	10.36	335.8	1.43
1989	16.13	60.06	8.31	323.9	.84
1990	16.14	56.02	13.08	249.7	2.63
1991	16.88	54.93	9.04	190.5	2.02
1992	14.97	58 10	9.27	230.8	1.32
1993	14.97	61.98	7.28	399.5	.66
x	16.90	57.78	12.30	315.9	2.26
stdev	1.20	3.07	2.47	85.03	1.17
var	1.37	9.43	6.13	7230	1.38

Preliminary indications show precipitation has greater influence on hectares burned than temperature. The ratio of hectares burned comparing dry and warm years is 5 : 2 . This is a crude result given the number of factors involved in total hectares burned and the simplicity of the categorization used. The category a certain year is placed in may not be a true reflection of that year's characteristics. For example, the timing of precipitation during a season is not involved in these statistics, only amounts are. As an example, 1958 was a dry year, but it received 72.1 mm of rain late in September. This did not lead to a change in categories, but almost doubled the entire seasons precipitation (200 mm for the season).

1970 was categorized a warm/very wet year, but fire consumed 14,000 hectares. Most of the precipitation occurred on one day, June 4th, which was preceded by five extreme fire weather days. The remainder of the fire season received precipitation on a regular basis, and the SSR was 2.95. Until June 4th, 1970 would be grouped as warm/dry; seasonally it is normal/very wet.

With a general categorization established, a more in-depth analysis of the data was developed. The number of days in a fire season rated as high danger have a strong influence on potential burning conditions. These days tend to occur together, due to past weather, and contribute heavily to total hectares burned. The next step examines the number of days per season which occur at various levels of danger. These days are delineated by the DSR. The DSR ranges from 0 to 75 over the entire data period. The majority of days in the fire season have a DSR below 10. Due to the influence of windspeed on the DSR, values above 10 tend to occur on days having high wind speeds.

Table 4.2 Seasonal description of fire seasons based on seasonal means and standard deviations of temperature and precipitation.

Year	Classification (temperature/precipitation)
1953	normal/dry
1957	warm/dry to very dry
1958	warm/dry to very dry
1961	warm/dry
1962	normal/wet to very wet
1963	warm/normal
1964	warm/normal
1967	warm/dry
1968	normal/normal
1969	warm/wet
1970	warm/wet to very wet
1973	cool/wet
1975	cold/very wet
1977	cool/wet
1984	cool/normal to wet
1988	cool/normal
1989	cool/normal
1990	cool/dry
1991	normal/dry to very dry
1992	cool to cold/dry
1993	cool to cold/wet

Table 4.3 Hectares burned per fire season. Brackets indicate the number of years in each category. Hectares burned is the larger number in each box.

	Wet	Normal	Dry
Cool	(4) 1,900	(3) 3,043	(2) 25,605
Normal	(1) nil	(1) 96,137	(2) 17,906
Warm	(2)13,857	(2) 3,098	(4) 6,600

The DSR is divided into three categories, depicting days of low, moderate or high danger. Table 4.4 is an example of this using DSR data from 1961. Different categories of fire danger were developed from analysis of fire weather data and the FWI. Because of the influence of the FFMC, its values were important when depicting danger categories. Low danger days are those with DSR's below 1.0. Moderate days have DSR's of 1, 2 and 3. High danger days are those with DSR's greater than three. These include days with DSR's of 5, 10, and 10+. The breakdown of danger classes using the severity index is similar to that used by Pouliot (1993).

Weather data from 1961 were used because it was a warm/dry year; it had an SSR index of 4.40, the highest over the 40 year study period. In 1961, 77 or 43% of the days in the fire season were classed high in fire danger. The same procedure was used for all fire seasons. Seasons with the same characteristics (ie. warm/wet) produced very similar tables. Noticeable variations occurred in the number of days in each danger level between years of contrasting general categories. This technique of describing the characteristics of the various types of fire seasons is a more specific method. It shows how a small change in the number of high danger days can affect the general category for a specific year, and illustrates how temperature and precipitation influence fire danger.

Table 4.5 shows the number of days in each danger class averaged for similar type seasons. An average of all seasons is similar to the season categorized as normal/normal. This occurred even with the normal/normal season having only one occurrence in the data. Warm temperatures produce more days in the high danger class than precipitation seasons which were considered dry (bottom row). These results are different than those calculated in Table 4.3. Table 4.3 indicates that precipitation may have more of an influence on the number of hectares burned than temperature.

Hectares burned and the total number of days in each danger class are different entities. Only a few continuous high (extreme) danger days are required for conditions capable of burning large numbers of hectares. The actual amount that does burn depends on many other factors.

This procedure can be used for the calculated SSR for each type of fire season.

The interpretation of the data in Table 4.6 might suggest that temperature may have more of an influence on the resulting SSR for a fire season than precipitation. Warm seasons have a significantly higher SSR than seasons categorized dry. In all seasons, other than the year categorized as normal/normal, the SSR increase proportionally through the table. 1968, (norm/norm) has the number of days expected in each DSR danger class, but a higher than expected SSR because only 18.8 mm of precipitation fell before May 24.

Table 4.4 Breakdown of fire danger days based on DSR for the year 1961. In this categorization days with a DSR < 1.0 are low danger days (35%); those with a DSR from 1-3 are moderate danger (22%); and those with a DSR > 3.0 are rated as high danger (43%).

DSR	Number of Days
0.25	43
0.50	14
0.75	8
1.0	7
2.0	23
3.0	11
5.0	29
10.0	25
+	23

Table 4.5 Danger days per fire season based on the categorization scheme.

	Wet	Normal	Dry
Cool	(4) 73 L 20 M 7 H	(3) 52 27 21	(2) 50 27 23
Normal	(1) 57 31 12	(1) 49 28 23	(2) 47 30 23
Warm	(2) 52 23 25	(2) 43 26 31	(4) 35 25 40

Bracket indicates number of years in each category.
Danger Class (number of days in % of season)
L - Low danger days
M - Medium danger days
H - High danger days

Table 4.6 SSR for fire season type, based on precipitation characteristics (horizontal) and temperature (vertical).

	Wet	Normal	Dry
Cool	0.77	1.29	2.01
Normal	1.43	3.43	2.06
Warm	2.38	2.92	3.87

Warm temperatures and high wind speeds occurred before May 24. During the last five days before annual convective precipitation began, the DSR averaged 40.4. FFMC's were extreme, having ratings between 92 and 95.3, and relative humidity values averaged only 20%. These five days were sufficient to raise the SSR value to a level higher than expected for the entire season. At this time, 96,137 hectares burned.

In contrast, but supporting the evidence that temperature may have a stronger influence on fire danger, is the fact that cool seasons have lower SSR's than wet years. Lower temperatures impede fire danger to a greater extent than seasons with abundant precipitation. Fewer number of high danger days occur during cool and normal years as well. More hectares have burned in cool years, but this can be attributed to one year in particular. 14,000 hectares burned (2 fires) in August of 1990, a cool/dry year. This is another example of fire's unpredictability.

These techniques demonstrate how various fire season characteristics are influenced by temperature and precipitation. Daily time series of fire weather then had a climate change scenario imposed on them. These scenarios are to determine what impacts there would be on fire danger for various types of fire seasons. The same categories used above are applied in the climate change scenarios.

4.4 CCC GCMII Scenario

To observe the potential impact climate change may have on fire danger for the study region, the scenario generated from the CCC GCMII was superimposed onto each fire season. The same techniques used to analyze the original data were utilized on the climate change data series. This was used to identify what type of season will be most affected by climate change, how much change in SSR's occur, and what climatic variables are most important under the changed climate scenario.

Table 3.1 shows the amount of change for the selected climate variables in the Lac La Biche region.

Other scenarios, including changing the timing of precipitation, were also run to determine their impacts on fire danger. For reasons given earlier, only temperature and precipitation values were altered. Their impact on fire danger has already been determined. Daily temperatures were increased depending on the month, and precipitation values were offset (%) by predicted increases or decreases. Initially, the CCC GCMII scenario was run using the same daily time series used above. Table 4.7 show the changed percentages of days in low, moderate, or high danger classes for the different season types.

SSR's for each type of fire season resulting from the

CCC GCMII scenario were also calculated and are shown in Table 4.8.

The CCC GCMII scenario increased the average SSR 37.5% from the original data. Cool and wet years experienced a greater change in SSR, increasing 42%, whereas all other years increased 36%. These results are similar to the findings of Flannigan and Van Wagner (1990). They calculated a 46% increase in the SSR using output from 3 GCM's for six locations across Canada but did not include the month of April in their study. Table 4.9 shows the change in the number of days in each class (CCC GCMII minus original).

The greatest change occurred in seasons of normal temperatures. The number of days in the high danger class increased 10%. The length of the fire season in this research (April to September) is 183 days. With a 10% increase, 18 more days of the season can be rated as high danger. These days mostly occur during June, July, and August because precipitation is expected to decrease 3%. This time period also coincides with the lightning season in the study area. Lightning fires which become problems are inclined to occur in remote areas and are usually responsible for the majority of hectares burned. Fire danger and the number of hectares burned should increase for seasons with normal temperatures.

Table 4.7 Danger days per fire season resulting from CCC GCMII output imposed on daily time series. Values are percentages of days in low (L), medium (M), and high (H) danger.

	Wet	Normal	Dry
Cool	64 27 9 +2	54 L 23 M 23 H +2	40 30 30 +7
Normal	50 32 18 +6	42 24 34 +11	38 27 35 +12
Warm	45 24 31 +6	39 26 35 +4	28 24 48 +8

The positive number indicates the increase in the percentage of high danger days.

Table 4.8 SSR for seasons with CCC GCMII scenario.

	Wet	Normal	Dry
Cool	1.08	1.89	2.85
Normal	2.05	4.50	2.86
Warm	3.38	4.02	5.12

Normal seasons occurred in 4 of the 21 years studied. Increases in the total number of high danger days for all scenarios. This fact alone may infer increases in the number of hectares burned in the future.

Dry years also show large increases in the frequency of high danger days, but not at the same magnitude as normal temperature years. Cool years showed least change along with warm and normal precipitation years. Of the study seasons, 38% are categorized as dry years. Changes in precipitation amounts resulting from the CCC GCM scenario are not large or small enough to alter a season's category. Currently, most precipitation occurs in the June-August period. The CCC GCMII scenario anticipates a decrease in summer precipitation, therefore amounts would remain relatively constant. The forecasted decrease in precipitation during the summer months is balanced by the increase in amounts in the spring and September. If dry seasons continue to occur with a climate change, there will be an influence on fire danger with an increase in the frequency of high danger days.

Table 4.9 Change in the number of days in each danger class in pecentages (CCC GCMII minus original).

	Wet	Normal	Dry
Cool	-9 +7 +2	+2 L -4 M +2 H	-10 +3 +7
Normal	-7 +1 +6	-7 -4 +11	-9 -3 +12
Warm	-7 +1 +6	-4 - +4	-7 -1 +8

4.5 **Influence of Individual Variables on the FWI**

4.5.1 Original Data

The previous section described potential changes to some general characteristics of fire seasons. It described how an increase or decrease in temperature or precipitation can alter fire danger for the season. The objective of this thesis is to study evaporation in a forest environment and its relationship to fire danger. One means of accomplishing this is to study fuel moisture. Changes in fuel moisture over daily, weekly, or on a seasonal time period, is an indication of evaporation. Researching which climatic variables influence soil moisture may determine how climate change may affect evaporation rates within the boreal forest and fire danger.

This section will examine the influence individual variables have on the CFFDR (FWI) system and the FWI's response to climate change. Discovering the effects modifying one variable has on the SSR, how the individual codes (FFMC, DMC, and DC) are influenced, and potential changes to soil moisture conditions for the study site are the objectives.

4.5.2 Individual Influence of one Variable on the SSR

To determine the influence a single climatic variable has on the SSR, one year, 1968, was chosen for study because it contained normal/normal. Four climatic variables were altered and the SSR recalculated.

The sensitivity of the FWI model to changes in individual climatic variables is calculated in Table 4.10. The information in the table may lead to the conclusion that increasing temperature has the greatest impact on SSR. An increase in mean surface temperatures of one °C increases the SSR by 5%. It is unwise, though, to compare changes in degrees, kilometres and percentages in order to determine which variables have the most influence on fire danger. Changes in the number of days in each danger level may be a more appropriate means of detecting the importance of each variable.

Table 4.10 Influence of Variables on SSR. Values are compared to the original value of 3.42.

	Temp (°C)		RH (%)		Wind (km/h)		Precip (%)	
Scenario	+1	-1	+1	-1	+1	-1	+10	-10
SSR 1968 3.42 Actual	3.60	3.01	3.14	3.47	3.53	3.09	3.18	3.53
SSR sce/act Change %	1.05 +5%	.88 -12%	.92 -8%	1.01 +1%	1.03 +3%	.90 -10%	.93 -7%	1.03 +3%

The following relationships were found to exist between climate variables within the CFFDR(FWI) system and the resulting SSR:

1) T+1° C is proportional to RH-2%
2) T+1° C P-10%
3) T+1° C W+1 kmh
4) RH-1% W+1 kmh
5) RH+1% P+10%
6) W+1kmh P-10%

It is more reasonable to compare frequency of days in each danger class, resulting from changes to each climate variable, to original data. The results are seen in Table 4.11.

Table 4.11 Change in the number of days in each danger class resulting from changes to individual variables.

	Temp (°C)		RH (%)		Wind (km/h)		Precip (%)	
Original	+1	-1	+1	-1	+1	-1	+10	-10
89 L	-6	+3	+2	-2	-5	+3	+3	-4
52 M	-2	-	-	-2	+1	-1	-1	-4
42 H	+8	-3	-2	+4	+4	-2	-2	+8

The number of days in each danger level show a temperature increase of one °C has the same effect as decreasing precipitation by 10%. A decrease in relative humidity of 1% is also proportional to an increase in wind speed of 1 km/h. These results reflect the drying power each variable has on the forest fuels and are not linear for changes in variables. For instance, the drying power of one degree (C) is proportional to a decrease in precipitation of 10%, but a 10 degree increase is not proportional to a 100% increase in precipitation. Only small changes are proportional.

This relationship is verified in Figures 4.1 and 4.2. Moisture contents of the fine and medium fuels are similar when the climate variables are changed according to the proportions outlined above. Very little difference exists in moisture contents. The fine fuel moisture contents are almost indistinguishable for all variables. Very similar results are produced with moisture contents representing medium fuels. Windspeed is not involved in the calculations for the DMC, therefore its moisture content remained at normal values for the season. Seasonally averaged moisture contents of the two fuel layers are listed below.

Fuel type	T+1°C	RH-2%	W+2kmh	P-10%
Fine fuels	30.94%	30.06%	30.89%	30.69%
Med. fuels	188.3%	189.4%	192.6%	186.1%

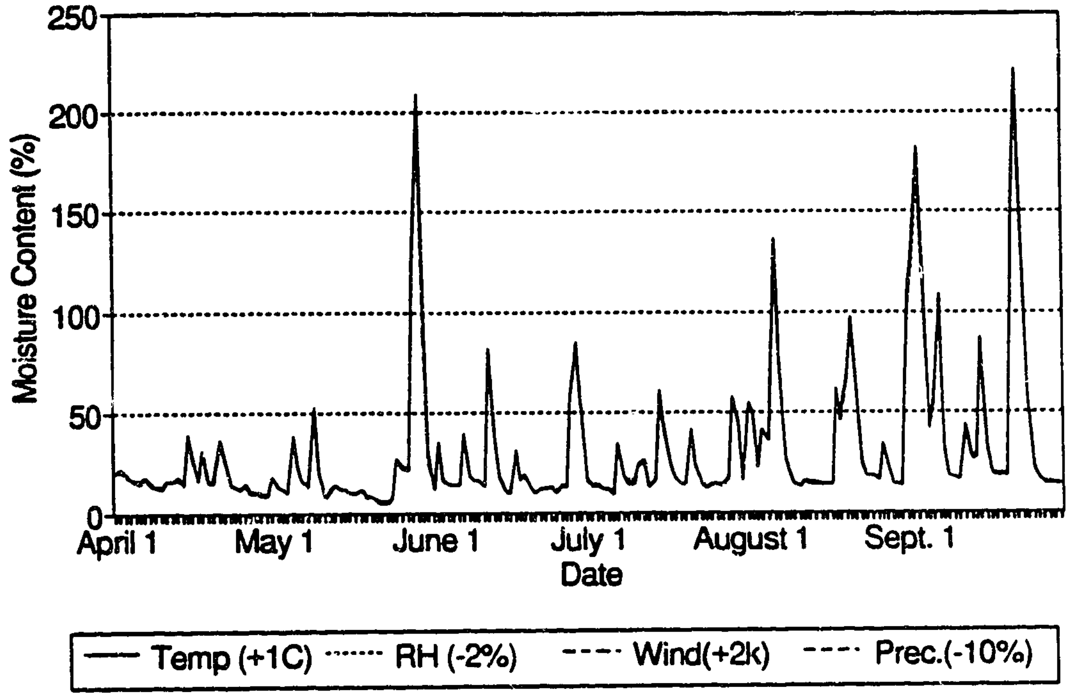


Figure 4.1 Moisture content of the fine fuels with various changes to individual variables.

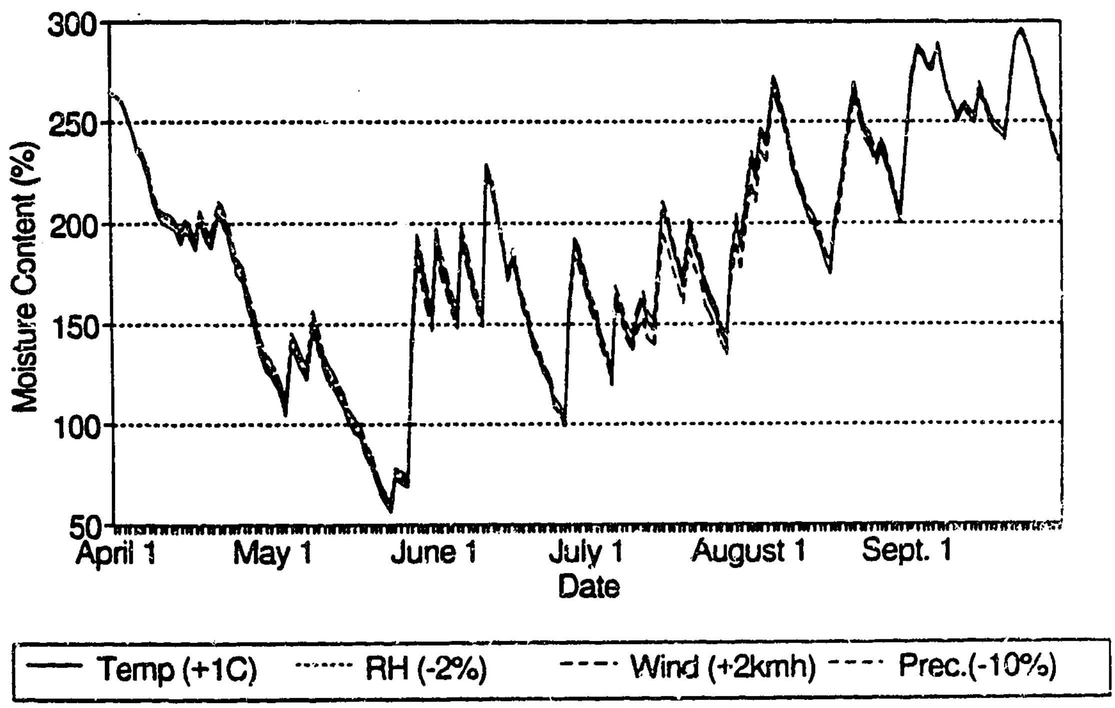


Figure 4.2 Moisture contents of medium sized fuels (DMC) with various changes to individual variables.

4.6 Correlation of FWI Variables

FWI variables, individually and in combination were correlated against data representing hectares burned per year. In fire research regression values comparing fire weather to hectares burned are low (Flannigan and Van Wagner 1991). The number of hectares burned depends on more variables than fire weather alone. Initial attack effectiveness (human error), length of the fire season, number of fires per day, fuel availability, and forest type are all important in determining how many hectares burn. Although correlations of fire weather versus area burned in other studies (Flannigan and Van Wagner 1987) found correlations that range from 0 to 42%, even low correlations show a relationship between the two.

Data were standardized for individual values for each fire season using climatic means, and regressions were calculated against the standardized values of area burned.

Fire data does not follow a normal distribution. Gathered fire data incorporates the number of hectares burned from only E-class fires (>200 ha.), and consequently some seasons show no hectares burned. Archived data of fire records for the Lac La Biche region collected from their Forest Office were used to complete the data base. Some seasons experienced very few hectares burned (<100), whereas in 1968 almost 100,000 hectares burned in the Lac La Biche

Forest. This type of data strongly influences regression output.

Data were placed in two categories. The first correlation was calculated using all of the 21 chosen fire seasons. The second set correlated fire weather against fire seasons where hectares burned were greater than 1900 hectares. These are referred to as Big fire seasons. Regressions found are in Tables 4.12 and 4.13. (Note: All fire seasons were correlated with and without 1968 data. 96,000 hectares burned that year and had a strong influence on the data.)

Stronger correlations occur when climate variables were correlated against Big fire seasons. Climate variables may have a less important influence on the number of hectares burned when all seasons are analyzed together. In contrast, Big fire seasons appear to be more strongly influenced by climate variables farther from their mean, especially temperature.

The influence of temperature on hectares burned is strongest. Correlations are higher when 1968 is omitted from the regression, but relationships are obvious even when 1968 is included.

R^2 values describing the influence of precipitation are not as high as expected, perhaps because the timing of precipitation is not included. A regression was performed involving the start date of the rainy season to determine its influence on the number of hectares burned. It revealed no relationship existed between the date of the beginning of the rainy season and the number of hectares burned in a fire season.

Table 4.12 Correlation values for all fire seasons. Significant at the 0.90 level.

All Seasons	R^2 (with 1968)	R^2 (without 1968)
Temp.	.0022	.0036
R.H.	.042	.016
Wind	.111	.105
Precip.	.009	.016
ALL	.249	.247
SSR	.083	.054
T & RH	.046	.016
T & W	.167	.155
T & P	.009	.017
P & RH	.044	.021
P & W	.124	.128
RH & W	.125	.108

Table 4.13 Correlation Values for Big Fire Seasons. Significant at the 0.95 level.

Big Fire Seasons	R^2 (with 1968)	R^2 (without 1968)
Temp.	.155	.478
R.H.	.013	.206
Wind	.067	.010
Precip.	.019	.070
All	.531	.752
SSR	.000045	.249
T & RH	.16	.664
T & W	.36	.725
T & P	.19	.636
P & RH	.123	.224
P & W	.067	.075
RH & W	.132	.230

An R^2 value of .0024 was produced. The beginning of the rainy season was defined as the time when more than 10mm of precipitation fell over a continuous 2-3 day stretch and when fire danger does not climb back to previous highs. The majority (p=.5) of rain commencement dates were between Julian day 140 and 160 (May 17 and June 5).

Temperature alone, or in combination with another variable, has the strongest influence on the number of hectares burned. The strongest correlation is achieved when it is combined with average windspeed. As temperatures are expected to rise with climate change, this relationship will become increasingly important. Even with increased precipitation, higher average surface temperatures may lead to higher SSR's, as in the CCC GCMII scenario described above. A study of moisture codes and contents with original data and the climate change scenario may reveal this relationship.

4.7 Fuel Moisture Codes and Moisture Content

Fire danger is ultimately based on evaporation and resulting fuel moisture content. This thesis examines the effects of weather on fuel moisture characteristics. The FWI model contains equations that allow calculation of the estimated moisture content of these fuels. Moisture content samples gathered in 1993 were compared to those estimated by the FWI. Minor differences existed. Actual moisture contents followed the same pattern the FWI model predicted, but the sites spruce stand, and in particular the duff layers, appeared more sensitive to changes in weather.

Selected seasons were used to determine the influence precipitation and temperature have on moisture code values. The CCC GCMII scenario is used to determine how these codes are influenced by an increase in mean surface temperatures and changes in precipitation patterns and amounts. Depending in what month precipitation occurs, this scenario produces either an increase or decrease in the amount of seasonal precipitation. Increases in precipitation tend to be larger than decreases on a percentage total. Seasons experiencing more rainfall during the summer months should see a decrease in seasonal totals because CCC GCMII output indicates a 3% decrease in amounts over this period. Years with wet springs and falls occur less frequently, but see an increase in seasonal precipitation totals. In general the amount of rain during the fire season (under CCC GCMII scenario) is very close to original totals. Thus, temperature may have a stronger influence on the moisture values of the forest fuels if the timing of precipitation remains unchanged.

Original moisture code values are plotted against daily precipitation. This illustrates how fuels respond to precipitation events of different magnitudes, and the response to extended periods of little or no precipitation. Examples are seen in Figures 4.3 to 4.6. These show the trends of the FFMC, DMC, and the DC, to precipitation events during the 1993 fire season.

All precipitation affects the FFMC. The surface layer (and fuels) is in direct contact with the atmosphere and thus is influenced to a greater and faster degree than the DMC and DC. Because the FFMC represents the surface and the fine fuels, diurnal changes occur in the moisture content of this layer. The surface layer changes its moisture content dramatically with any amount of rain, and appears to have a maximum moisture content around 200% by weight (1993 data).

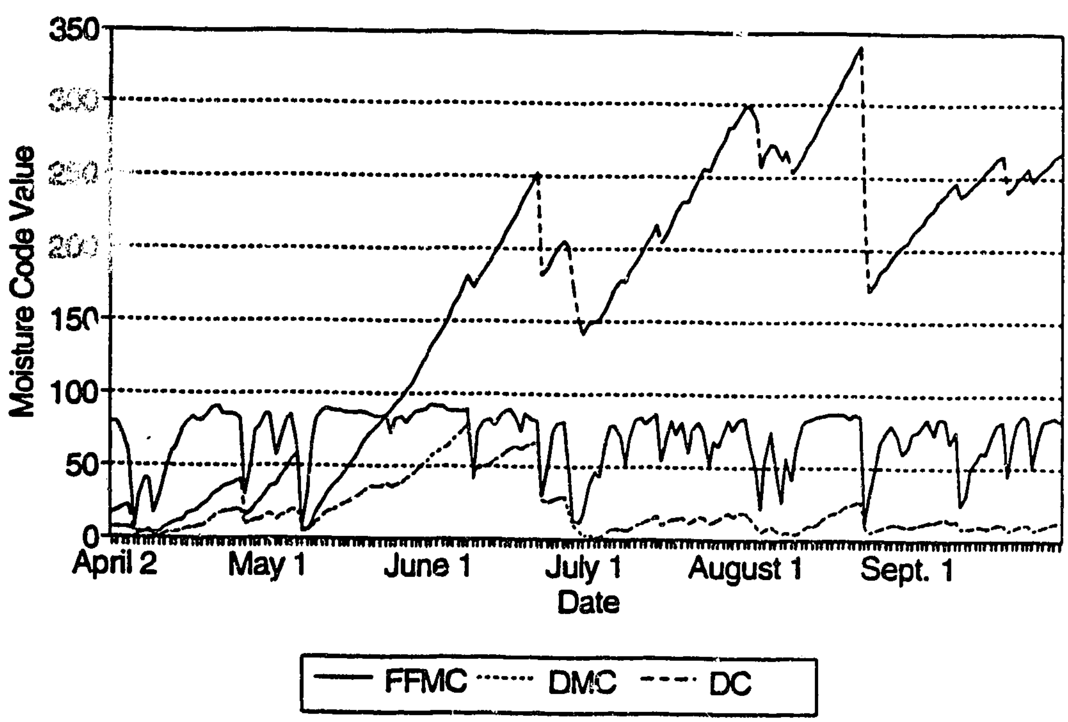


Figure 4.3 Estimated moisture code values using original 1993 fire weather data.

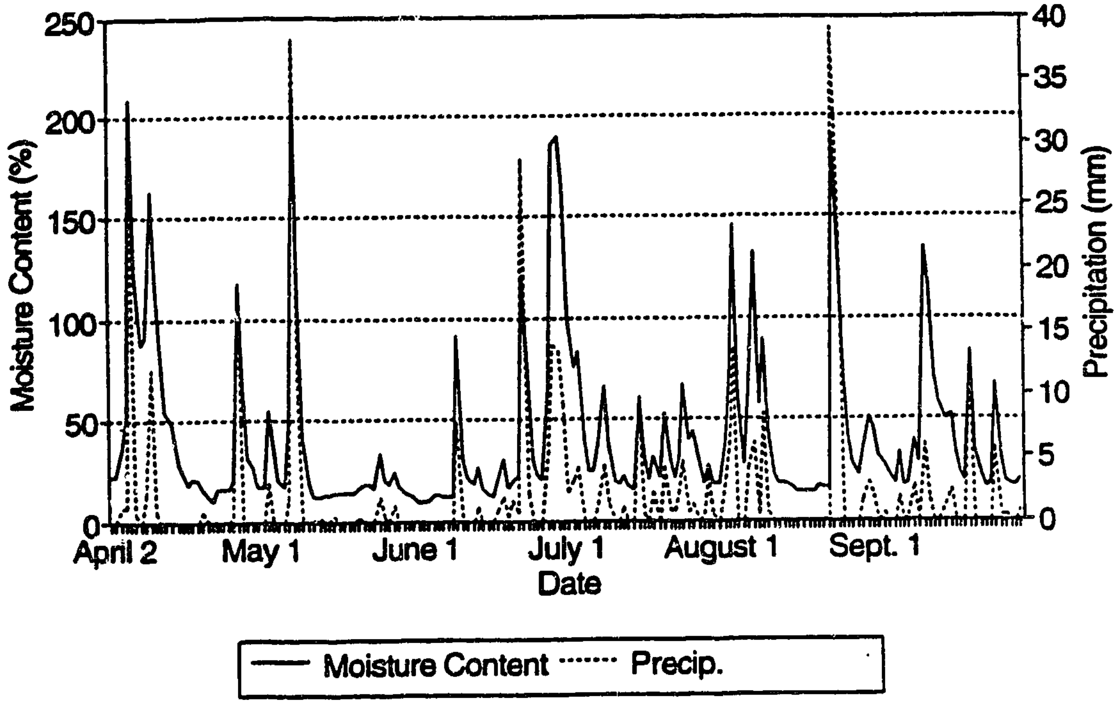


Figure 4.4 Comparison of estimated FFMC values and rainfall.

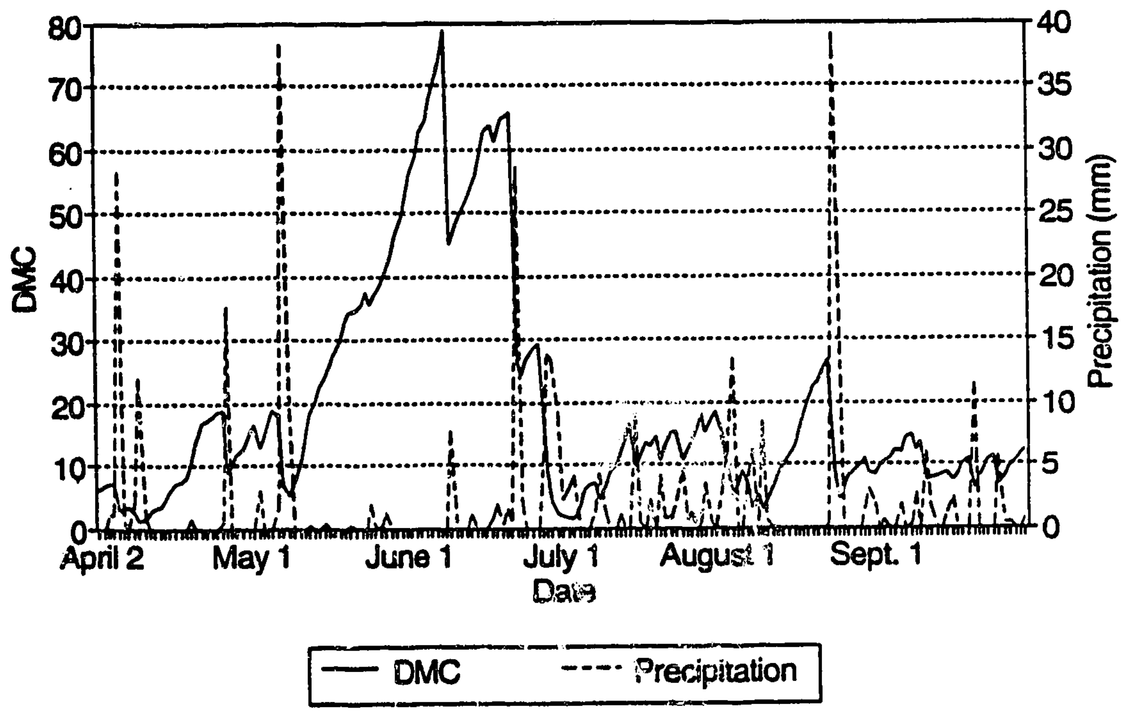


Figure 4.5 Estimated DMC values and rainfall.

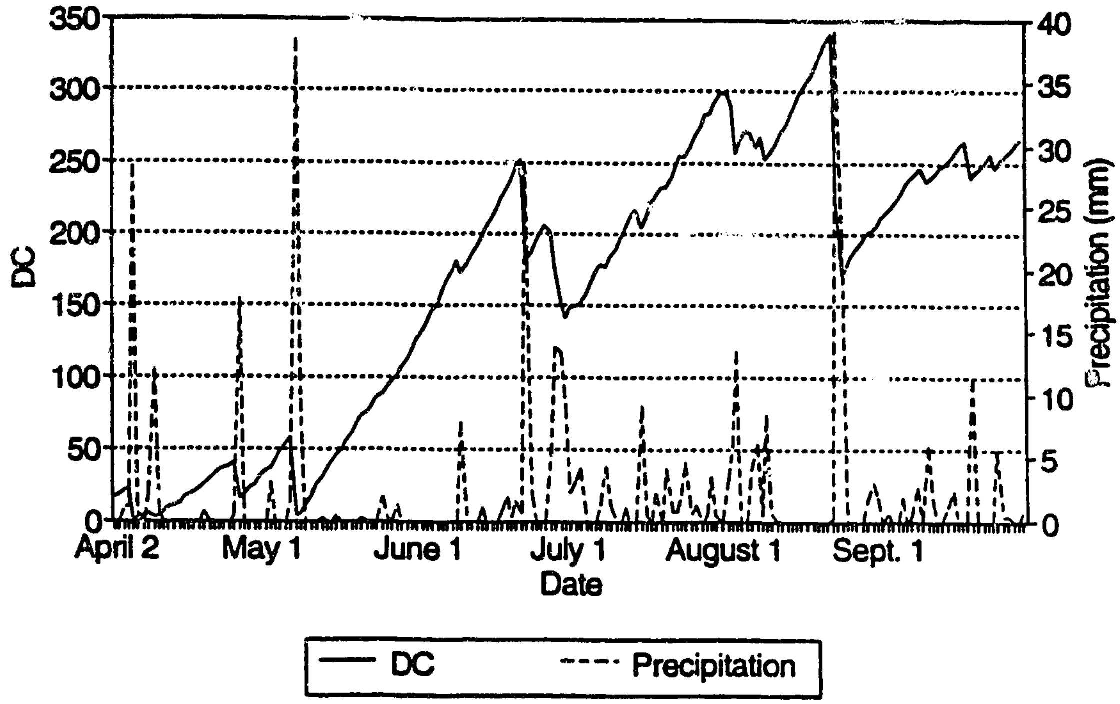


Figure 4.6 Estimated DC value and precipitation.

Fuel moisture contents can vary from 200% to 25% over a three day period (See Figure 4.4, May 10). Daily fire danger rises and falls depending on moisture contents of the surface layer. High danger begins when the moisture content of this layer approaches or goes below 18% by weight. During the 1993 fire season this rarely occurred.

Moisture contents of the DMC layer ranged from 290% to 70% by weight, for the 1993 season. Precipitation had an almost immediate effect on the moisture contents of this layer as seen in Figure 4.5. Since the timelag (amount of time required for a fuel to reach an equilibrium moisture content under constant conditions) is much longer for this layer than the fine fuels, more time is required for the DMC index to climb. Figure 4.5 shows that the time required for moisture contents to change from 265% to 65%, by weight, was approximately one month. With the CCC GCMII scenario, the DMC value would increase to 92 instead of 79 over this period (Figure 4.8). Increased temperatures have a large impact on the moisture content of the DMC layer, making available greater amounts of fuel to fire.

The moisture content of the DMC layer is important to lightning hazard. In the CCC GCMII scenario, DMC values are considerably higher than the original data. The potential for greater number of lightning ignited fires exists if climate change occurs. Calculations show that average moisture contents may experience large changes.

The CCC GCM scenario was run and compared to original fire season data (Figures 4.7 to 4.9). Moisture contents of the DMC layer decreased from 186.8% to 170.2% for 1963 data (warm/normal); from 197.4% to 175.2% for 1988 data (cool/normal); but remained at 195% for 1970 data (warm/very wet). These variations corresponds to an average increase in the DMC index of 6.5 points. Decreases of this kind in normal or dry precipitation seasons, will have an impact on possible future fire scenarios.

The Drought Code is representative of long term moisture conditions for a particular site. The general pattern exhibited by the DC, over the summer, is to gradually increase as the lower soils dry out. This pattern existed in the 1993 season to some extent, even with abundant precipitation. The DC started at a very low level due to spring saturation, but increased slowly. Setbacks occurred after major precipitation events, but the DC continued to climb during smaller rainfall events. After heavy rains (>25mm), the DC would drop nearly one-half its pre-rain value. The maximum value achieved by the DC in 1993 was 340; lower than most seasons.

The scenario derived from CCC GCMII output increased the DC value (seasonal average) by 40 points. The maximum value for 1993 data under this scenario was 400. These increases were more dramatic during the summer months with less precipitation. The increase in DC values over the fire season is evident in Figure 4.9. This figure c[illegible]s the CCC GCMII scenario to original data repres[illegible] data. The deeper duff layers are experiencing [illegible] contents through the entire season. A [illegible]nt of fuel is now available to fire indicat[illegible] of deep burning, stand destroying fires. [illegible] depletion may be carried over-winter, an[illegible]ght conditions may exist, also increasing the numbers of hectares available to fire.

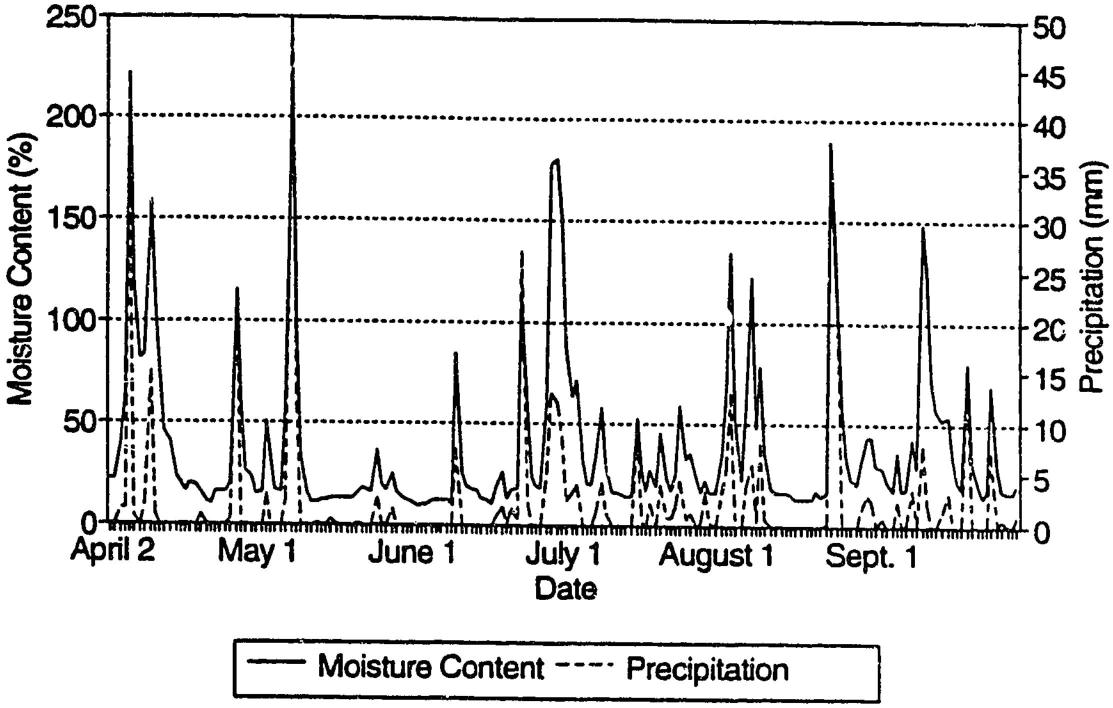


Figure 4.7 FFMC response to CCC GCMII scenario.

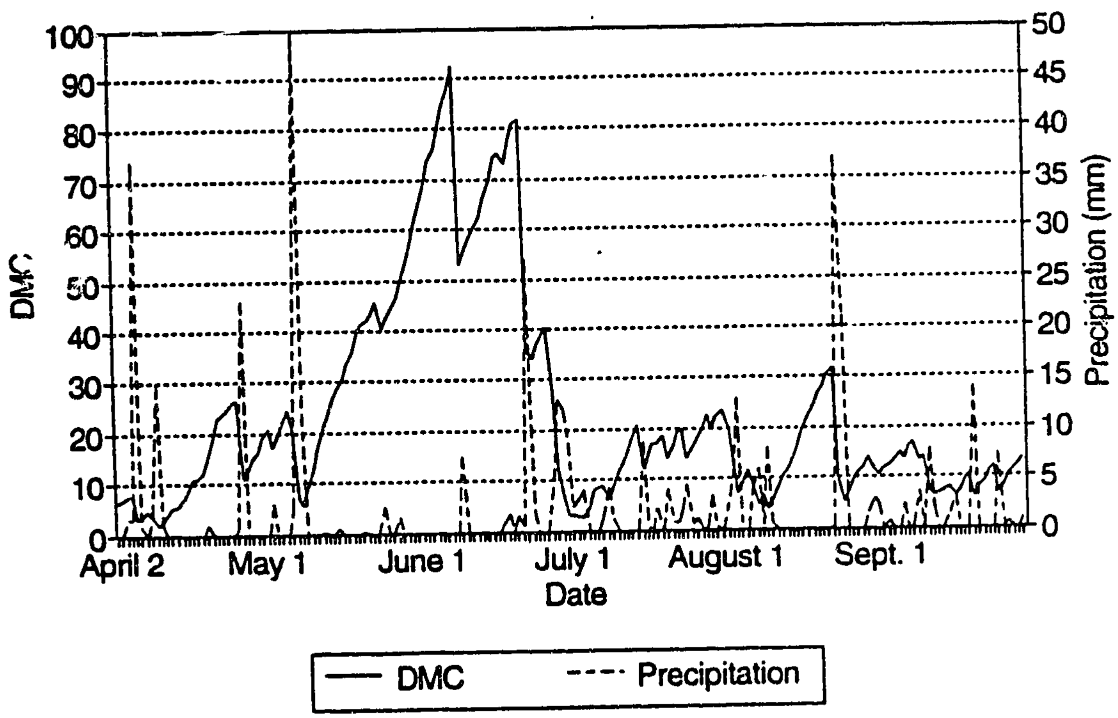


Figure 4.8 DMC response to CCC GCMII scenario.

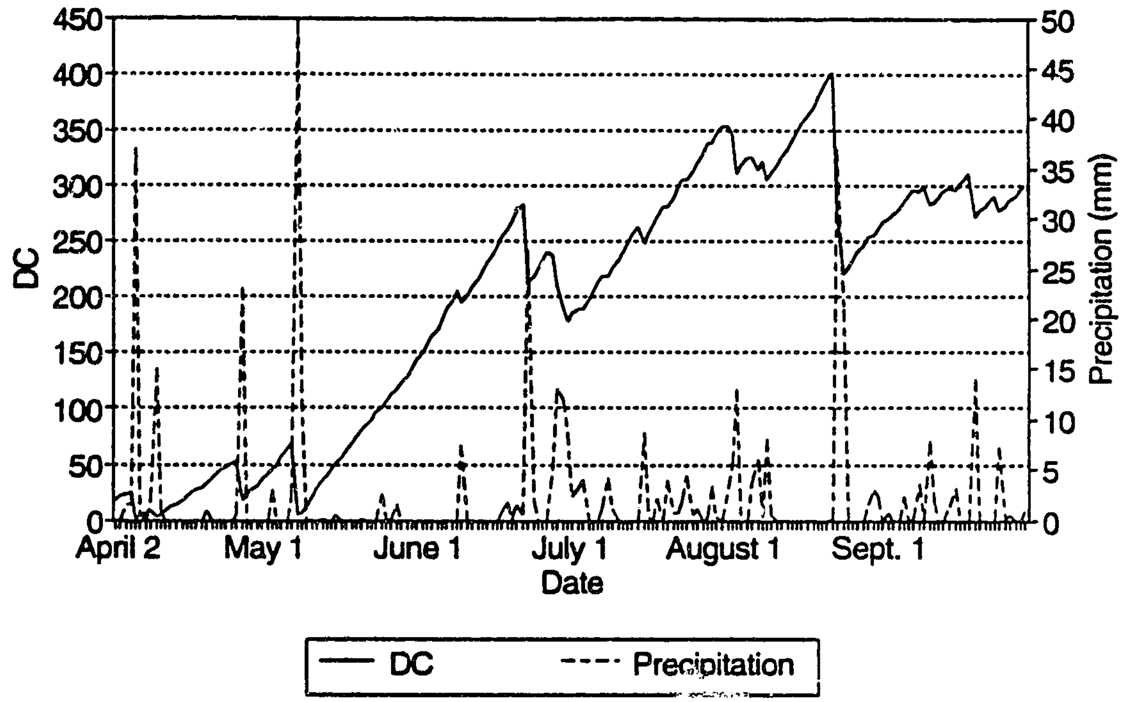


Figure 4.9 DC response to CCC GCMII scenario.

4.8 Altered Precipitation Scenarios

A number of seasons had the timing of initial summer precipitation altered. The beginning of the rainy season was moved farther back into the summer to determine the impact on fire danger. Time series from 1963 (warm/normal), 1970 (warm/wet), and 1988 (cool/normal) were chosen for this scenario. Original data were analyzed and the beginning of precipitation was altered (moved ahead) between 7 and 10 days. 1963 and 1988 were run in combination with the CCC GCMII scenario, whereas 1970 used original data only.

Curren ly, GCMs are unable to determine the timing of rainfall events. They produce monthly values indicating total precipitation expected for each month. This may be considered weather forecasting, instead of climate change prediction, but the timing of rainfall is paramount in creating the fire danger for a location. Therefore this caveat is applied to impart the importance of precipitation timing, and to suggest 'what if'.

4.8.1 **1970 Data**

The 1970 fire season had high to extreme fire dangers until June 4th. The spring was very dry and all indices climbed at a consistent rate. The five days preceding June 4th experienced extreme fire danger. 1970 was chosen to see how one extra week of dry spring conditions would affect already extreme dangers. The first major rain event was moved ahead 10 days, to June 15th, according to Robock *et al.* (1993). The impact on the moisture contents of the FFMC and DMC, and the DC index are shown in Figures 4.10 to 4.12. The greatest impact is on the DMC. Moving precipitation caused moisture contents to fall from 60% to 35% (by weight) over this period (See Figure 4.11). Original moisture contents of 60% already produced extreme fire danger. By decreasing an additional 25 percentage points, the number of hectares able to burn may increase dramatically.

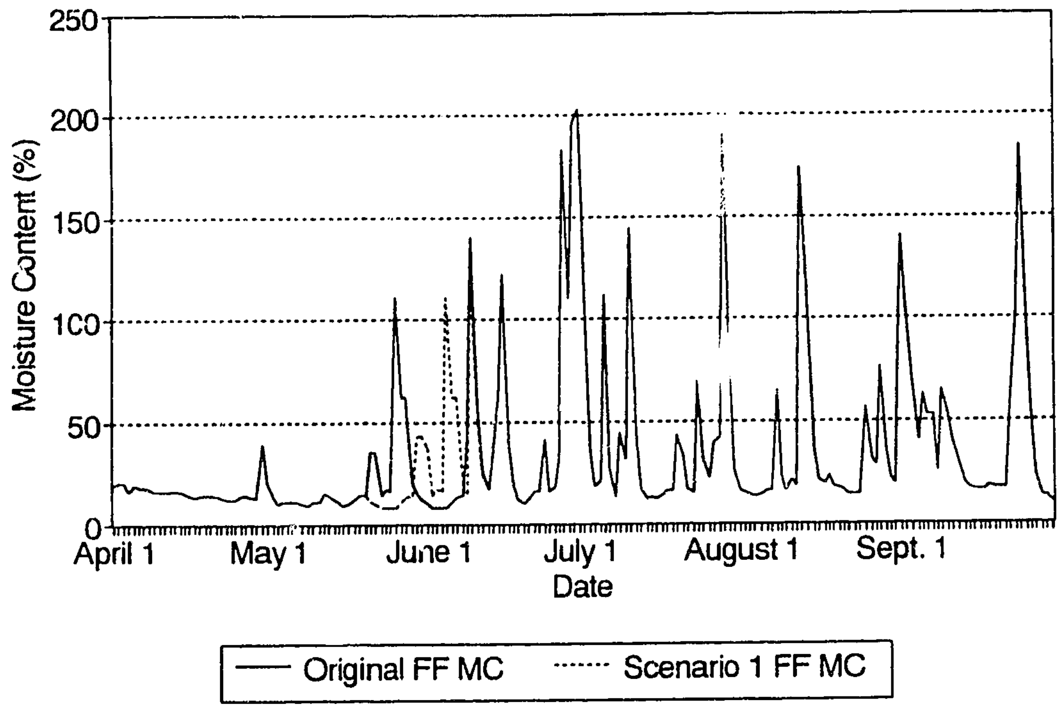


Figure 4.10 Influence of precipitation timing change on FFMC for 1970.

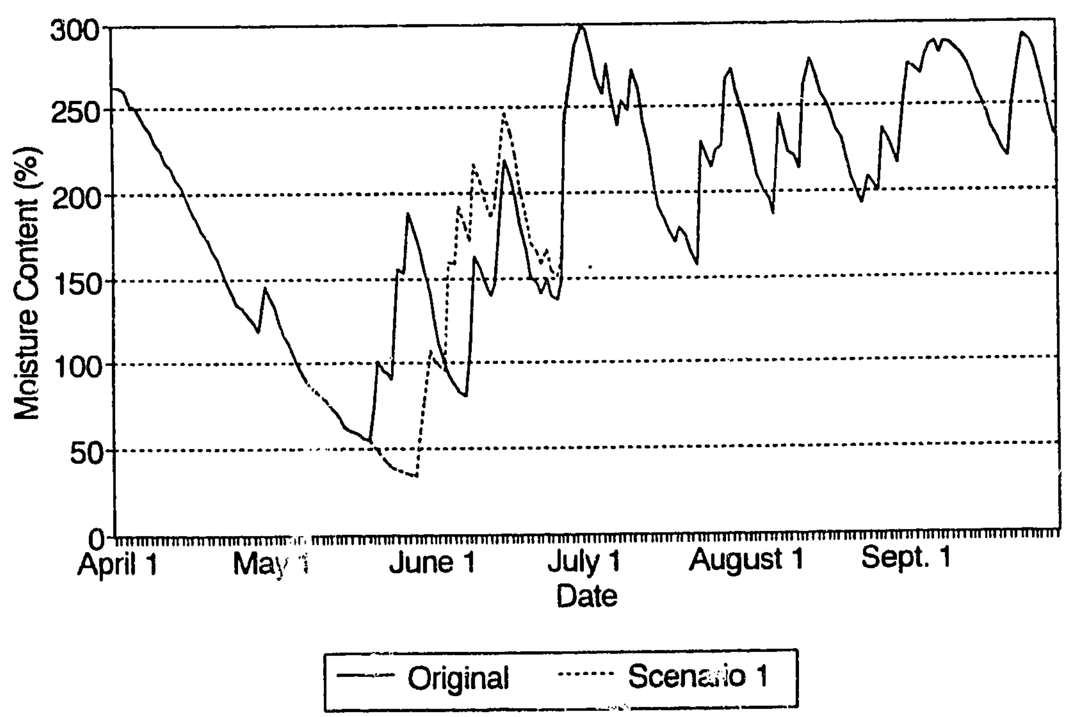


Figure 4.11 DMC response to change in precipitation timing (1970).

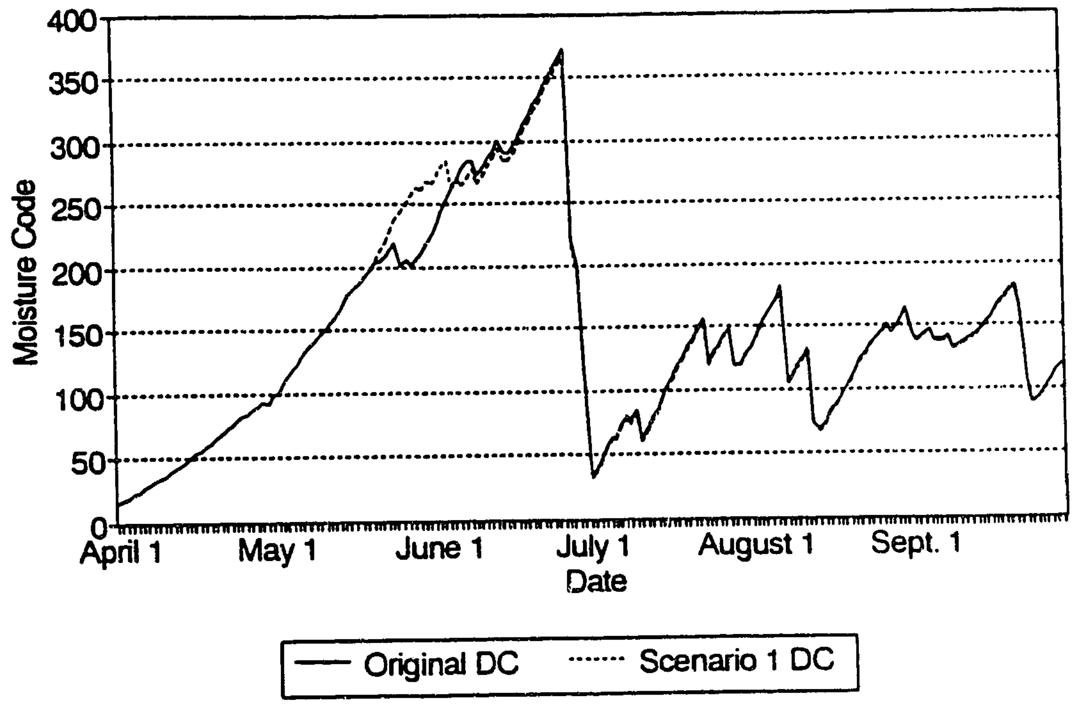


Figure 4.12 Response of DC to change in precipitation timing (1970).

When combined with FFMC values, which remained unchanged, an already extreme danger increased by an extra 10 days.

The DC was affected moderately. Values rose an additional 60 points over this ten day period (See Figure 4.12). Even with a long time-lag, this layer experienced considerable drying of its fuels.

The SSR under this scenario was also affected. 1970 original fire weather data produced a SSR of 2.95. By moving the start of the precipitation season forward 10 days into the summer, the SSR increased to 3.21 (an increase of 8%). All climate variables maintained the seasonal statistics of the original data, but seasonally, the fire danger rose from a medium to a high danger rating.

Such a scenario would have a large impact on the fire environment. Extremely dry fuels would allow the fire danger to climb to levels rarely achieved in the Lac La Biche region. This scenario was run without the CCC GCM output imposed onto it. The fire weather experienced in 1970 was severe, but would have been even worse if spring dry conditions had lasted an additional 10 days. The next two scenarios were run with the timing of the rain altered, along with the climate change scenario.

4.8.2 **1963 Data**

The impact of combining a climate change scenario with a change in the timing of precipitation is profound. With 1963 data, the SSR climbed from a value of 2.51 to 3.58. Late June precipitation was moved forward seven days and changed the moisture content of the soils enough to produce high danger values.

In this scenario, FFMC values were similar to the original data, as shown in Figure 4.13. Only after precipitation events were there noticeable differences in moisture contents, and then only in the summer months. Summertime moisture contents were roughly 10% lower in the climate change scenario.

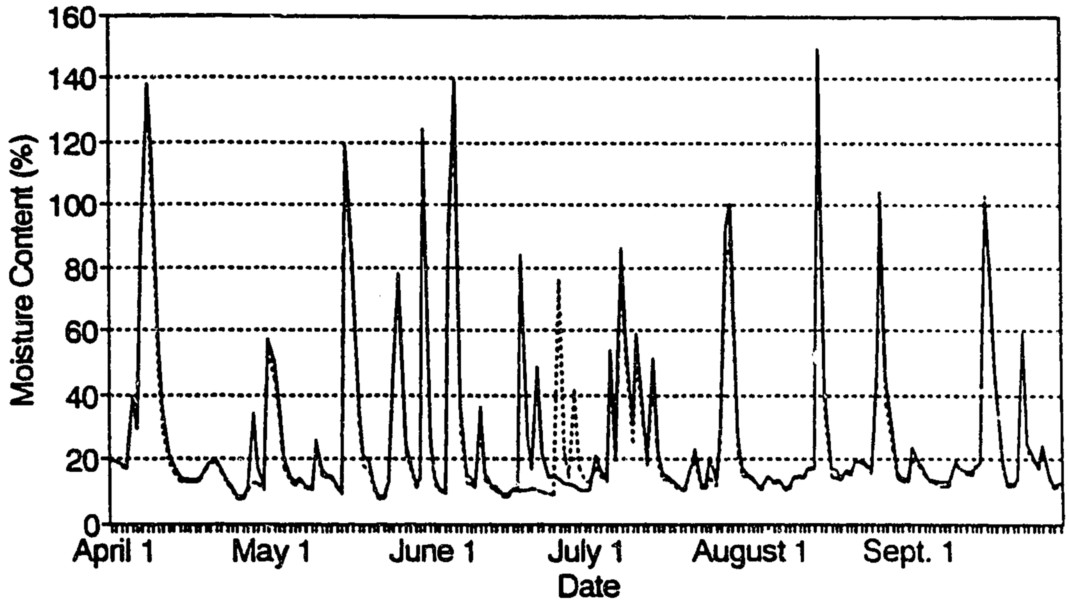


Figure 4.13 Response of FFMC to change in precipitation timing (1963).

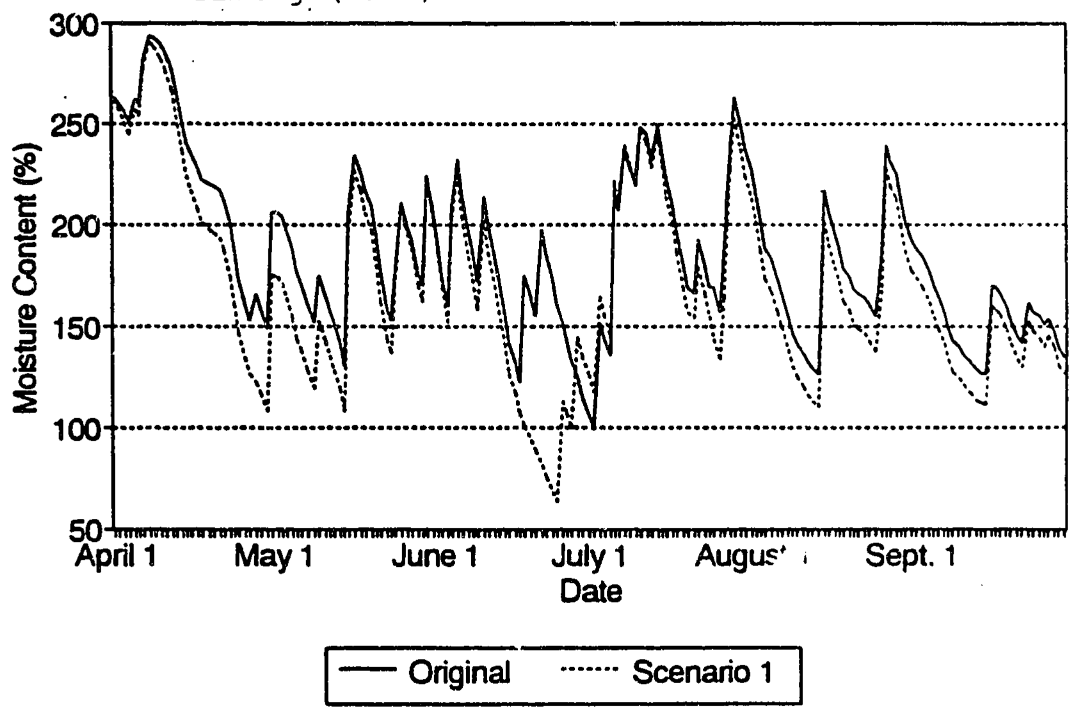


Figure 4.14 Response of DMC to change in precipitation timing (1963).

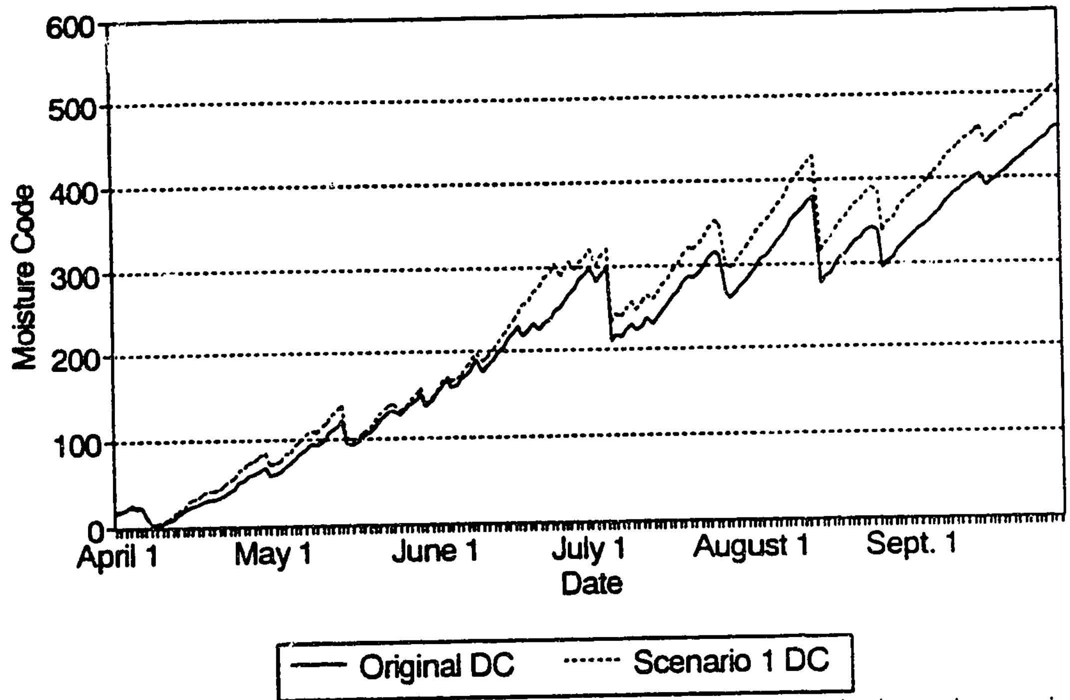


Figure 4.15 Response of DC to change in precipitation timing (1963).

This was due to 3% less rain, and an increase in surface temperatures. Moving precipitation ahead resulted in an extra week of moisture contents at 13% for the surface fuels. During the remainder of the summer, moisture contents were one to two percent lower than those of the original data.

The moisture content of the layer representing the DMC was considerably lower for the entire fire season in the CCC GCMII scenario. Differences were larger during stretches of dry weather because fuels were drying at a faster rate. Increased temperatures and less rainfall during the summer months added to these differences. Moisture contents changed as much as 40% following p-riods of little precipitation; otherwise differences averaged 15%. Moving rainfall ahead into the season allowed moisture contents to drop 40% lower than those of original data. After the rain, moisture contents remained 40% lower than the original data. Moisture contents during this period approached 60% (by weight) as seen in Figure 4.14; this range reflects extreme conditions.

1963 was categorized as a warm/normal season. There were 30 more days of high danger than in the original data, even with 11 mm more precipitation. Just under one-half the days in the summer would experience high fire danger.

4.8.3 1988 Data

1988 was categorized as cool/normal. It had a SSR of 1.43 which is low danger. The CCC GCMII scenario, combined with an eight day change in the start of the rainy season, increased the SSR to 2.39 - a moderate rating. In this scenario, 28 more days of the fire season were classed as high danger: a change from 27 to 55 days for the season. Because 1988 had such a low danger rating, large changes in moisture contents resulted.

Over the fire season, FFMCs were slightly lower than the original data. Eight extra days occurred where moisture contents averaged 20%. These values are not extreme but were lower than what resulted during the rest of the season. One mm less precipitation fell in this scenario, therefore an increase in temperatures and a change in precipitation timing had a strong influence on danger ratings. Seasonally averaged moisture contents of the fine fuels dropped from an original of 27.5% to 24.5% (Figure 4.16) in the climate change scenario.

Moisture contents of the DMC layer declined 22%, on average, over the summer. Changes were greater after dry periods (approaching 25%), but maximum values were only 5% less than those from the original data. By moving the rain ahead one week, moisture contents of this layer dropped 50% (see Figure 4.17). The extra week of dry weather allowed moisture contents to drop from 100 to 50% (by weight) putting the fuels in a dangerous state. Fine fuels averaged 20% during the same period, producing high danger ratings. Figure 4.18 shows that during this same period the DC increased from 180 to 265. This combination would produce a large amount of fuel capable of burning.

On average, DC values increased 39 points under this scenario. During the extra week of no precipitation, its value went from 200 to 270. The amount of difference between the original data and the changed scenario, increased during the end of the fire season - a period of little precipitation. With increased temperatures the soil is depleted of its moisture storage more rapidly.

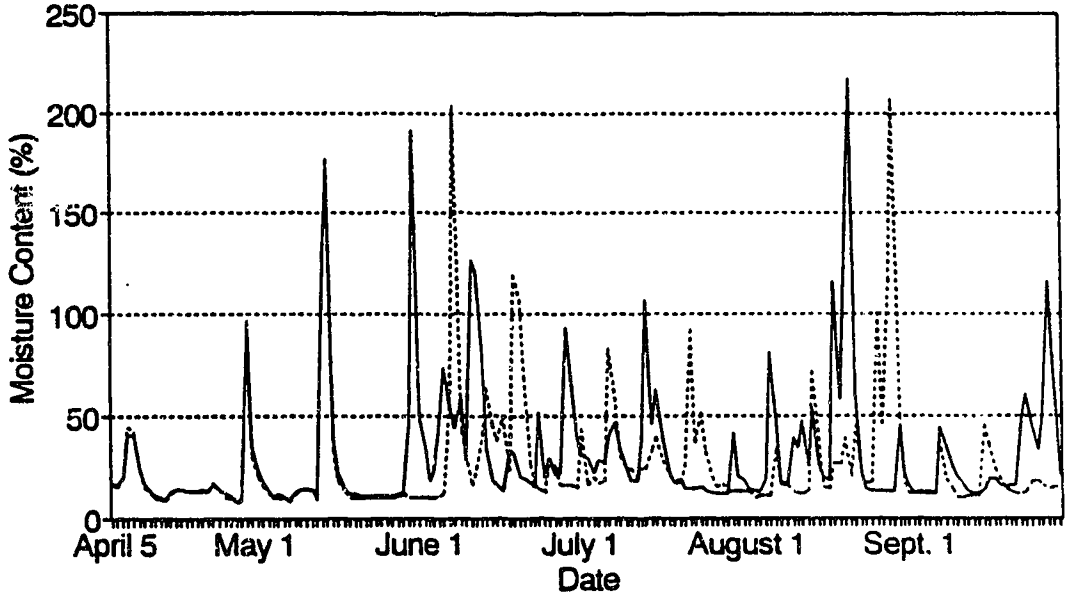


Figure 4.16 Response of FFMC to change in precipitation timing (1988).

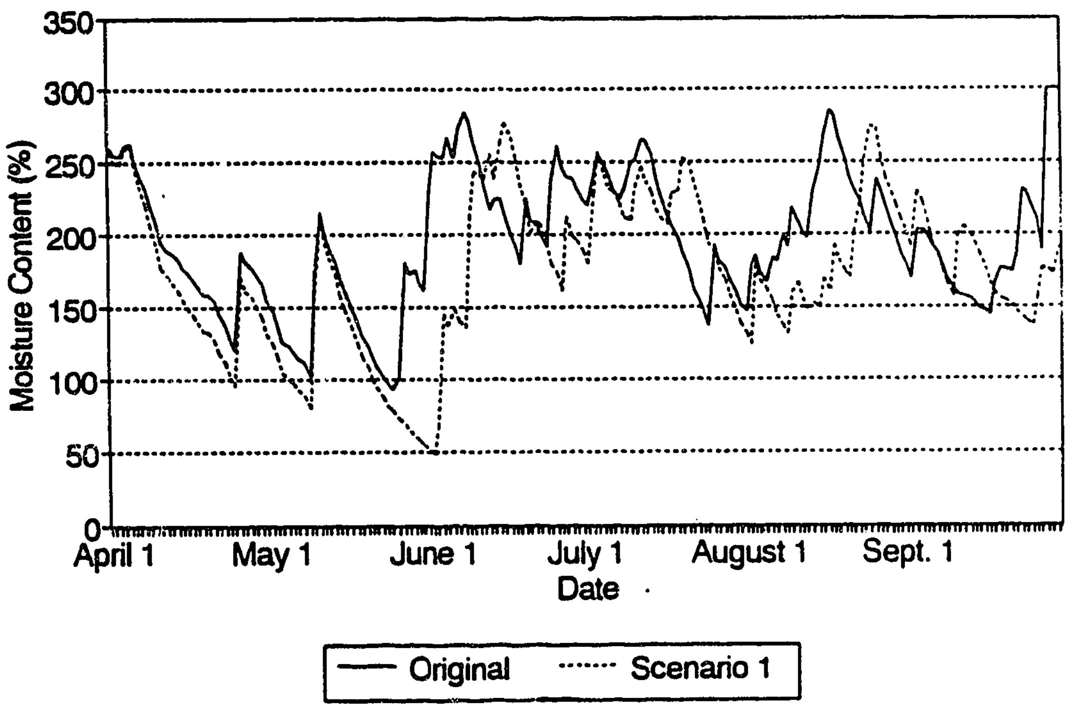


Figure 4.17 Response of DMC to change in precipitation timing (1988).

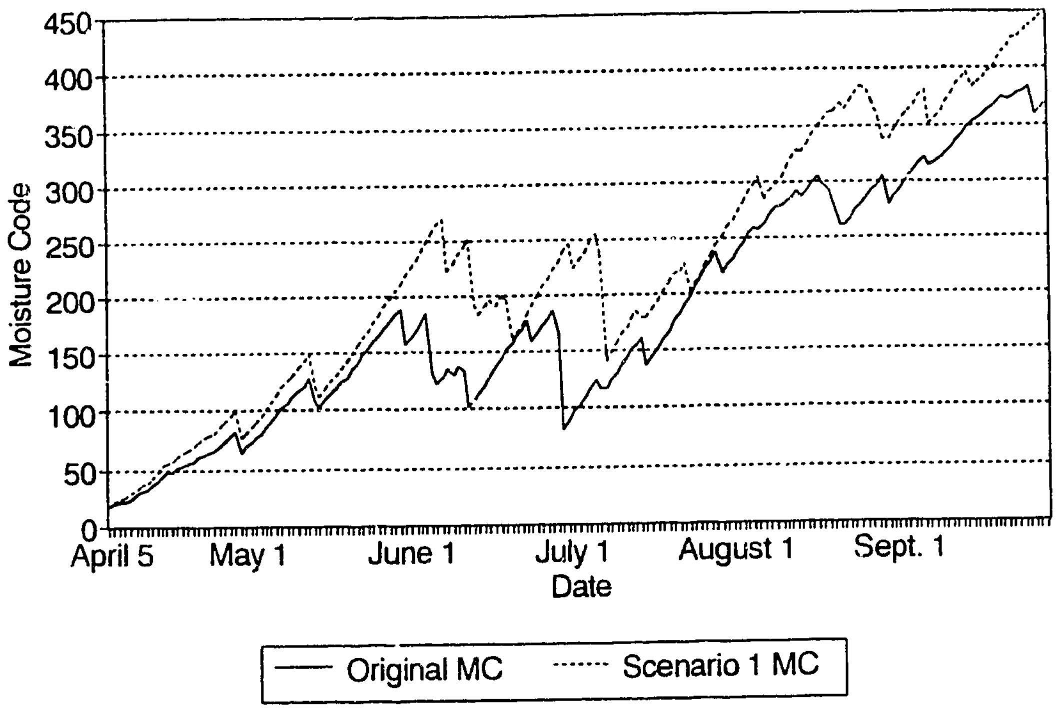


Figure 4.18 Response of DC to change in timing of precipitation (1988).

To conclude this section a few brief observations will be stated. Results of FWI sensitivity tests indicate that a climate change scenario may increase the number of high fire danger days by 18 over the length of the fire season. April and September were included in these scenarios to account for an increase in the length of the fire season. The fire season may experience a shift in timing when these high danger days occur. Presently the majority of high danger days, and the number of hectares burned, occurs in late spring and early summer. Under the CCC GCMII scenario, this period may move farther into the summer months, when less precipitation is predicted, and which coincides with the lightning season for the area. The CCC GCMII scenario used in this research resulted in moisture contents of the forest fuels declining by as much as 10% on average, even with increased precipitation in the spring and fall months. Temperature and precipitation were found to be the most important variables in describing the severity of fire seasons. The timing of precipitation during the course of the fire season is known to be important. The timing aspect was simulated by altering the timing of the start of the rainy season. Results show moisture contents of the forest fuels decreasing to extreme levels of danger. An extra week of drying in already dry spring conditions can lead to previously-unseen levels of danger, and result in many more hectares burning.

CHAPTER 5

Sensitivity of Evaporation Model

The one-dimensional physical evaporation model was tested using the same procedures employed for the FWI model. Season types were known from the categorization schemes used in chapter 4. The model was initialized for the study site and sensitivity tests were performed on the climatic variables as model input. Where the model appeared to be performing reasonably, climate change scenarios were run.

5.1 Model Initialization

Fire weather data available for the period 1953 to present is a collection of daily, noon value readings from Lac La Biche Forest Offices and A.E.S. stations. The model was initially developed for either an hourly or daily time step. An hourly time step is more precise, but the historic data will not allow this type of precision. Model output therefore describes trends in the evaporation process using the daily time step. Results of hourly versus daily time steps were performed in model development (Halliwell 1989) and both are accurate. One process lost as a result is the hourly evaporation that occurs from the surface fuels. Descriptions of evaporation rates following precipitation events of short duration are hidden in model output. Using the daily time step, this high evaporation rate was modified, and a precise rate was not produced. Initialized data sets are shown in Section 2.4.2 and 2.4.5.

Initial simulations used fire weather data from the 1993 season. Daily inputs of climatic variables were arranged in a format compatible for use in the evaporation model. These included: daily PAR values; noon values of temperature (°C), relative humidity (%), wind speed (kmh^{-1}), and daily precipitation (mm). The PAR values were multiplied by 2.5 to produce a net radiation value simulating Q* under the canopy. Relative humidity and temperature were used to calculate vapour pressure, wind speed converted to ms^{-1}, and, precipitation values were converted to meters. These operations were performed within the model.

Soil moisture values in the Halliwell model are calculated as volumetric moisture contents, in percent. FWI model values represent percent moisture content, by weight. Values produced by the two models are different, but the patterns produced over a season should be similar. The model was run with initial surface and soil moisture contents values of 0.85, or 85% moisture content by volume, to simulate spring saturation conditions. The FWI model can also have initial values of moisture contents set at the beginning of the fire season. Maximum moisture content values were set at 0.87 in the evaporation model for both surface and soil moisture conditions. Surface moisture contents change more quickly and dramatically than soil moisture contents, as in the FWI model. The surface layer (the layer for surface moisture), in the Halliwell model, is defined as being of arbitrary thickness. It reaches greater depths than that describing the surface in the FWI model, but it still reacts quickly to environmental conditions, though not to such a large degree as the FWI surface layer.

To run the evaporation model, a soil temperature profile was needed. A profile was approximated using previous daily temperatures and the mean annual temperature for the location. It represents an estimated profile from the surface to 1.5 m in depth. There are 50 nodes in the model representing the soil profile, each of which, requires a temperature value.

The profile is a realistic portrayal of the sites climate. Surface temperature was kept at 2°C (based on previous days temperatures), and decreased to zero degrees at -30 cm. The temperature then reached a minimum and returned to zero degrees at -50 cm (estimated frost depth). From -50 cm to -1.5 m in depth, the temperature warmed to the area's mean annual temperature, 1.2°C.

Values depicting time step, height of anemometer and temperature measurements, and surface roughness height were taken from site measurements. The first simulations used surface evaporation resistance coefficients already present in the model from Churchill data. Performance of the model to simulate site conditions with comparisons to FWI moisture contents resulted in adjustments of these values.

5.2 Initial Model Performance

The soil profile produced the disappearance of the zero degree isotherm by day 40 of the simulation (May 23). The temperature at -1.5 m was 8.15°C at the end of September.

The next procedure in model development was testing model sensitivity to air temperature data. Two data sets were tested: noon and mean daily temperatures. Surface and soil moisture content were analyzed to determine model performance. Figure 5.1 shows the change in moisture content of the soil using noon and mean temperature values. Soil moisture contents changed more quickly and dramatically when mean temperature data were used. Immediately after precipitation, soil moisture values decreased to unrealistic values as shown in Figure 5.1. In early May, soil moisture content changed from 0.83 to 0.73 (by volume) immediately following rain. Noon temperatures decreased soil moisture values from 0.83 to 0.78, a difference of only 5 percentage points.

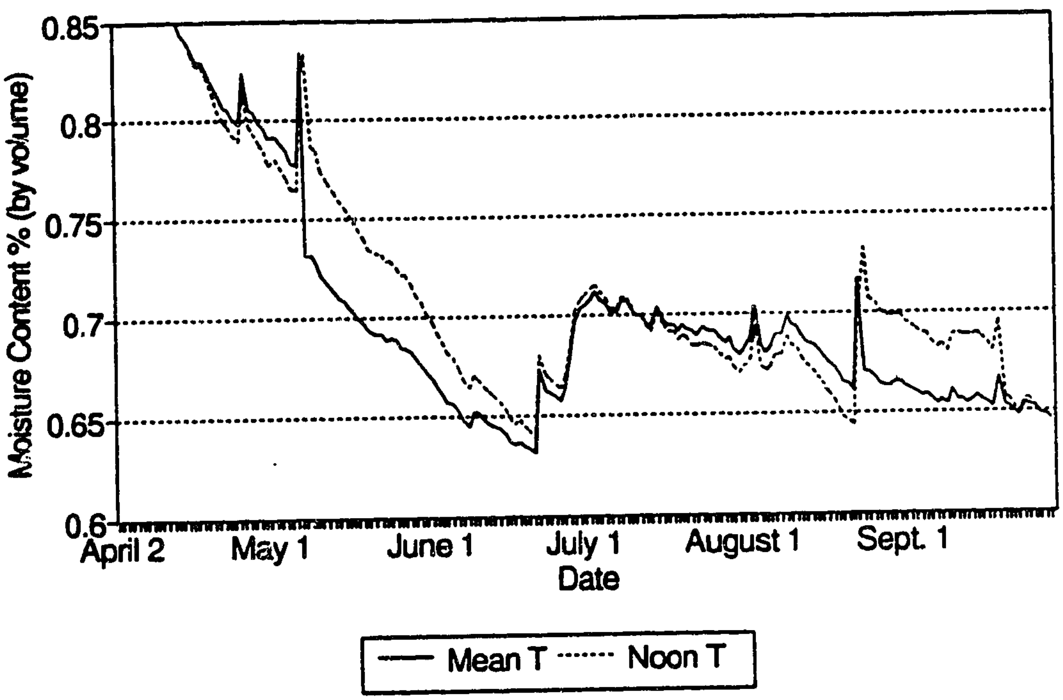


Figure 5.1 Soil moisture content using noon and mean temperature data sets

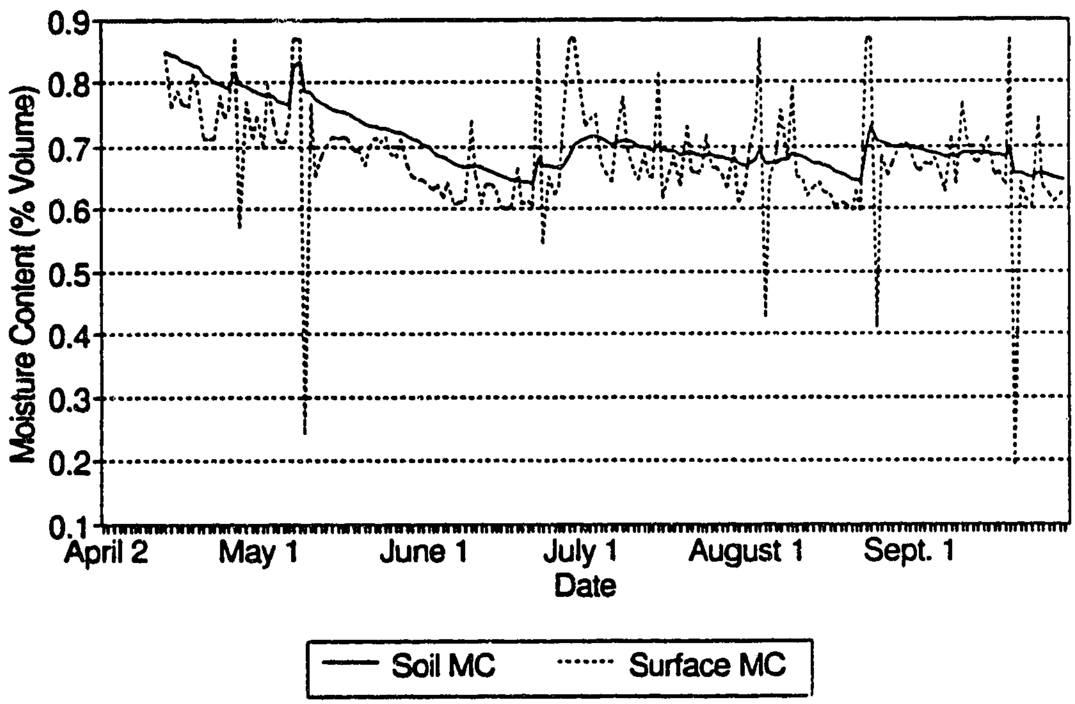


Figure 5.2 Initial soil and surface moisture contents.

This amount of change may be realistic for surface conditions, but the deeper soils should not be this sensitive. Figure 5.2 gives two examples. Twice during the fire season, surface moisture conditions are affected. In early May and late August surface moisture contents appear to dry too quickly, and by too large of volume. Moisture contents drop to values close to 0.2, immediately after heavy rainfalls. These large changes occur with rainfall events greater than 15 mm. The two large decreases occurred after rainfall events of 38 and 60 mm respectively. Decreases of this size are moderated using noon hour temperature values. Because of model response, noon hour values will be used in future simulations.

Model sensitivity of air and soil surface temperatures was also examined. It is expected that there would be a similarity between air temperatures and the resulting surface temperatures. Surface temperatures are expected to be marginally warmer (0.5°C) than air temperatures based on the temperature/height relationship but the difference is less than what would occur in open environments where there would be more intense surface heating. Figure 5.3 shows air and surface temperatures are very close. The soil profile is illustrated, as well as mean temperature data. The soil profile produced surface temperatures slightly warmer than the recorded air temperature. Surface temperatures using daily mean temperature data, show large decreases after heavy rain, with values even approaching the freezing point. This would indicate the process of the latent heat of freezing, and should not occur.

The temperature at the base of the soil layer was also examined using the above data sets. They were analyzed to determine if produced soil temperatures were either too warm or cold. The soil profile produced year end (September 30) temperatures that were acceptable. Late summer temperatures at 1.5m in depth peaked around 11°C. These values are similar to generalized soil temperature profiles produced by Oke (1987).

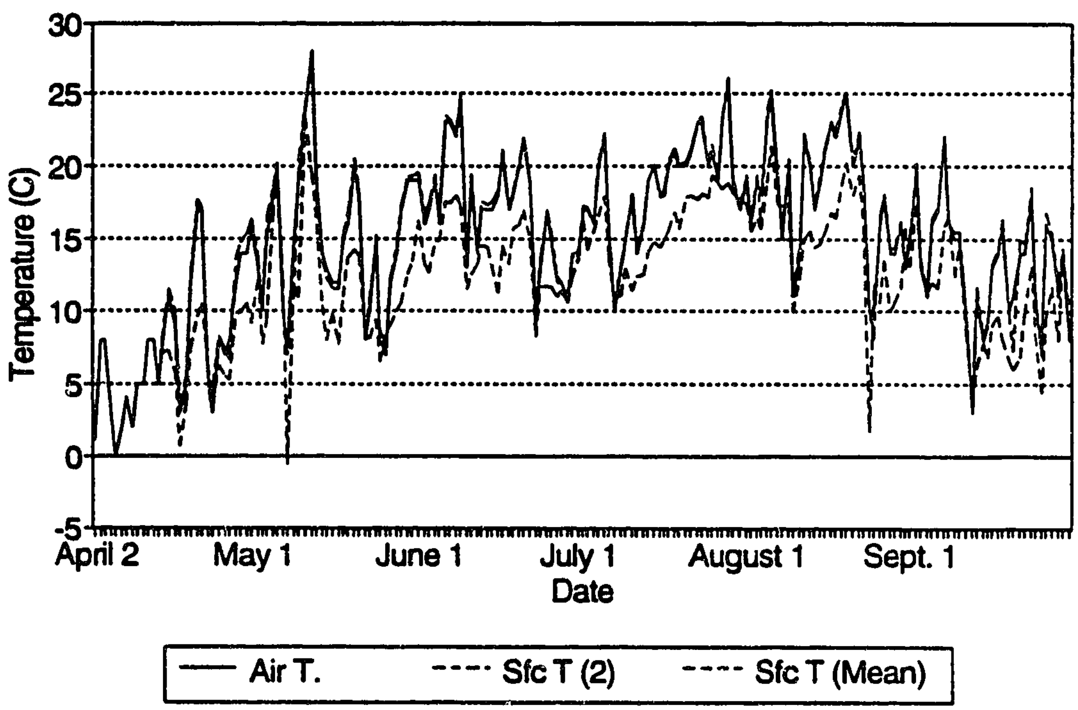


Figure 5.3 Air and surface temperatures from original simulation.

5.3 Comparison to FWI Model

It is not the goal of this thesis to adjust the evaporation model to replicate the results of the FWI model. Potential errors in both models would make this unwise. It would be encouraging, though, if both models produced similar moisture content patterns for a fire season. Preliminary comparisons of the two models, using the chosen initialization data sets, and produced results, were compared to DMC values from the FWI model (Figure 5.4). Similar moisture content patterns exist between the two models. Collected moisture content samples are also included in this figure. FWI moisture contents are more sensitive to precipitation than the collected samples reflecting model inefficiencies, or specific soil and site characteristics. Soil moisture content patterns respond almost identically to precipitation events and drying periods. The DMC layer, consisting of loosely compacted duff, increases in estimated moisture content (by weight) from 80 to 290% at the beginning of July (Actual from 70 to 190%). Over the same time period, the moisture content of the soil in the Halliwell model increased from 0.64 to 0.72 (by volume). The FWI model uses moisture contents of organic material to describe the DMC. Moisture contents in the Halliwell model corresponds to a depth that includes a combination of organic material and clay.

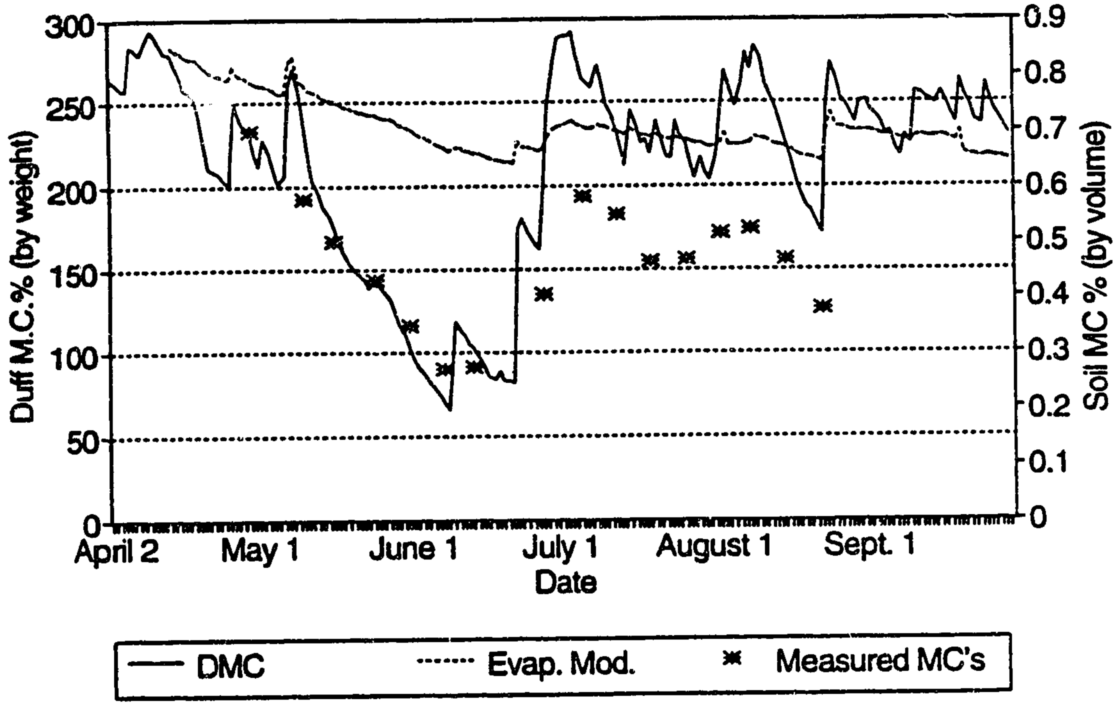


Figure 5.4 Comparison of estimated FWI and Evaporation models and measured soil moisture contents.

This 0.67m deep thick layer would lead to a slower response of the soil to precipitation events and to drying periods. The FWI model estimates moisture contents of three smaller, individual layers, to a depth of 20cm.

The similarity between the two models was encouraging and improved confidence in the use of the Halliwell model to simulate evaporation rates and fire danger.

5.4 Model Adjustments

Model response to large changes in soil moisture contents and surface temperatures after heavy precipitation was modified using daily noon temperatures instead of mean daily temperatures. Even with this adjustment, the problem of fluctuations still existed at a minor level. The rate at which moisture moves across the surface boundary and through the soil at deeper levels is controlled in the model by the resistance cycling coefficients, C1, C2, and C3. C1 represents the response of the model to evaporation and precipitation, and therefore simulates the surface layer. Its units are s/m^2 and it describes the resistance (r) of the surface to the movement of water. Initial values used in the model are 300,000 s/m^2.

C2 is the measure of the rate of return to an equilibrium value dictated by soil moisture at depth (Halliwell 1989), and has units of /m. C1 and C2 must balance, therefore if C1 is too large, evaporation will dry the surface faster than water is able to move upward and replace it (C2). After heavy rain, the surface moisture content would respond by decreasing to values indicating an extremely dry surface. Extremely high evaporation (QE) rates were calculated during days of heavy rain producing values greater than the ability of the model to replace this moisture. As a consequence, low surface moisture contents resulted. To eliminate this, C1 was decreased to 50,000s/m^2, and C2 to 0.1/m. Increasing the surface resistance lowered evaporation rates to levels where subsurface moisture could migrate upwards fast enough to replace the evaporated

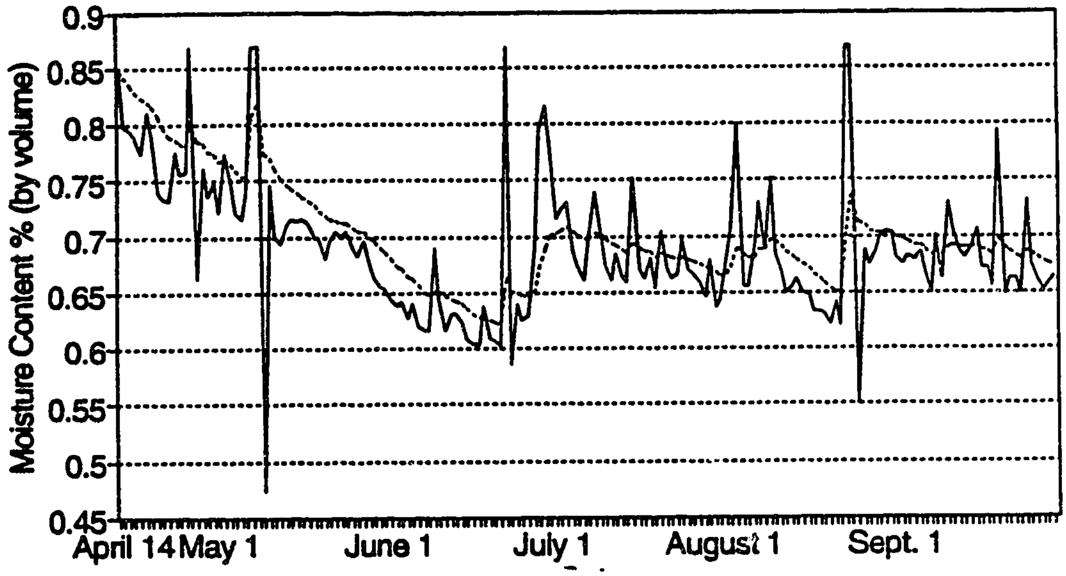


Figure 5.5 Surface and soil moisture contents using C1 = 50,000s/m² and C2 = .05/m.

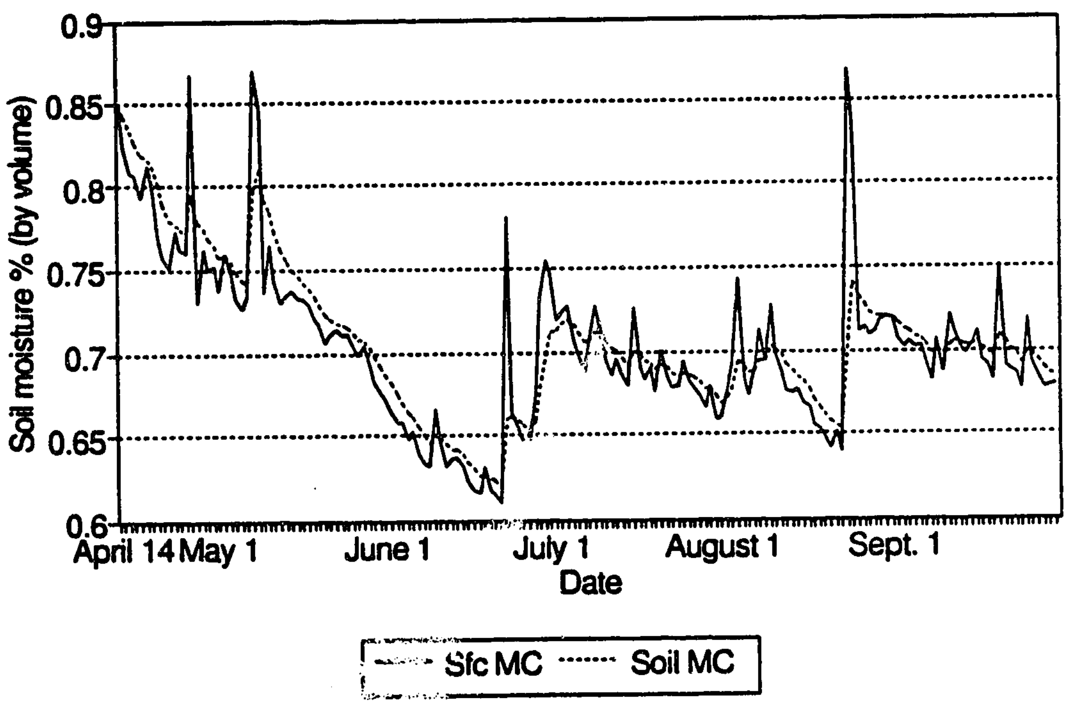


Figure 5.6 Surface and soil moisture contents using C1 = 50,000s/m² and C2 = .10/m.

surface moisture. Figures 5.5 and 5.6 show the change in the surface moisture contents resulting from modifications to C1 and C2. Surface resistance (rs) is low during rainfall, but increases to higher resistances the next day. This procedure produced rapid changes in surface moisture contents, but eliminated the large, one day fluctuations present in Figure 5.5 (Note May 10). The time step used in this model (daily) may be partly responsible for this process. An hourly time step would reveal high rates of evaporation during, and immediately following rain, but this may last only a few hours. The model would then move toward an equilibrium moisture content. With heavy rain (>15 mm), the model simulates intense evaporation, producing very low surface moisture contents.

C3 describes the depth of the layer being studied - in this research the value used is 1.5/m. 1/C3 should be equal to the depth of layer for soil moisture (0.67 m).

5.5 Sensitivity Tests

Once the model was set up, simulations using fire weather data were performed. Initially, 1993 fire weather data was input into the Halliwell model. This is followed with sensitivity tests to determine the models response to changes in individual climatic variables.

5.5.1 **1993 Simulations**

Simulations using fire weather data for the 1993 season were run using the soil profile, noon hour temperatures, and the adjusted resistance cycling coefficients (C1, C2, C3) described above.

The 1993 simulation provided the results listed in Table 5.1. Units for QH, QE, and Qg are Wm^{-2}, and are the mean values for the season (170 days). Thaw date indicates the disappearance of the zero-degree isotherm.

Table 5.1 Results of 1993 simulation. Values in Wm^{-2} are daily mean values.

Factor	Value
QH	49 Wm^{-2}
QE	77.9 Wm^{-2}
Qg	11.4 Wm^{-2}
Sfc. MC	.703
Soil MC	.707
Avg. Sfc. T	16.02
Thaw Date	May 19

QE can be converted to a water equivalent. Conversion of 77.9 Wm^{-2} over 170 days indicates a 422 mm water equivalency (Oke 1987). 400 mm of precipitation fell during the fire season, a [illegible]ence of 22 mm; an encouraging result. A possible [illegible] difference exists between evaporation and pre[illegible]n may be due to horizontal movement of water wit[illegible] the soil. The model was not developed with parameterizations describing runoff or drainage from the system. The landscape in the study area is relatively flat but runoff may occur. Along with this, the soil dried out over the season.

Surface and soil moisture values are shown in Figure 5.2. The most noticeable features are the response to rainfall events and the major drying trend that occurs during May. By lowering C1 to correct for the large amount of drying experienced by the surface after heavy precipitation, the surface layer is not responding to actual precipitation (wetting up) properly. C1 was developed to describe the gaining and losing of moisture. Before C1 and C2 were adjusted, the moisture content of the surface layer rebounded to maximum moisture contents (0.87) during rainfalls greater than 11mm. After adjustment of the coefficients, rainfalls greater than 20 mm (daily) are needed for the surface layer to return to near maximum moisture contents. Before adjustments were made to C1 and C2, maximum moisture contents of the surface layer occurred seven times. Figure 5.2 shows maximum moisture contents are reached only 3 times for the surface layer.

After a month of dry weather (mid-May to mid-June) rains of 28.6 mm were not sufficient to wet the surface layer to maximum moisture content. The adjustments of C1 and C2 create a situation where trade-offs have to be made. The response of the surface to rain events was determined to be more important than the surface reaching maximum water contents after rain.

Soil moisture contents in the Halliwell model appear to respond more realistically than surface moisture contents. During periods of dry weather, change is more gradual than that of the surface layer. The soil moisture value acted as a mean which the surface moisture content fluctuates around. Surface moisture contents change more quickly on a day to day basis, but tend to return to the moisture contents describing soil conditions.

The Halliwell model produced moisture contents at the end of the season that were drier than initial moisture contents. Soil moisture values decreased over the course of the summer from 0.85 to 0.68 (a ratio of 0.8). This may seem unrealistic due to the amount of rain, but it replicates observed and collected data. Collected moisture content samples also decreased (dried out) over this time period. Early season values of the DMC and DC were 235 and 180% moisture contents by weight, respectively. At the end of September they were 125 and 75% (ratios of 0.53 and 0.42). Even with abundant precipitation, a long term drying pattern resulted. The large difference in ratios is related to the thickness of the layer(s) being examined. As stated earlier, the Halliwell model simulates to a depth of 0.67 m, and includes the surface layer. The FWI is describing individually wrapped, thinner layers, thus producing larger changes in moisture content.

Average surface temperature was 16.02°C; 1.05°C higher than the average air temperature for the season. The difference between the air and surface temperature was very small on rainy days. Greater differences were experienced during dry days, when QH was large and Qg relatively small.

The date the zero-degree isotherm disappeared was May 19. Most energy in the model was used to thaw the soil during this time. In other simulations the seasonal value of Qg determined the thaw date (Table 5.2). A relationship existed between the seasonal summed value of Qg and the date of ground thaw.

Generally, the greater the value of Qg, the later the thaw date. More energy is absorbed by the soil and used to thaw the ground. This results in higher summed values of Qg for the season. This relationship is visible in Figure 5.7. Greater amounts of Qg occur in the spring, where it is used to thaw the soil.

Table 5.2 Qg (Wm^{-2}) Values for selected years.

Year	Qg	Thaw Date
1993	11.3	May 19
1991	11.9	May 21
1977	15.5	June 1
1990	24.8	July 13
1957	12.0	May 13

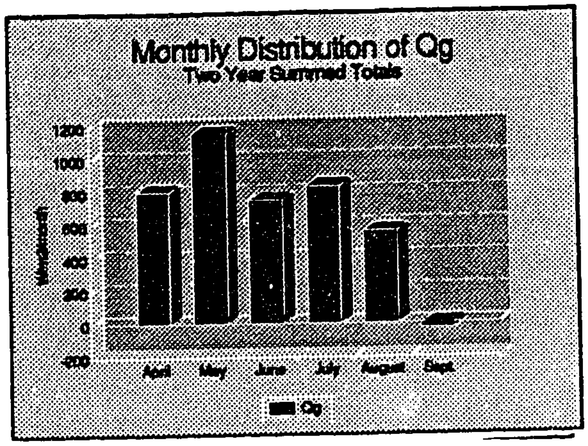


Figure 5.7 Monthly Values of Qg

5.5.2 **Model Sensitivity to Changes in Individual Variables**

The Halliwell model was then tested to determine its sensitivity to changes in meteorological variables. The Halliwell model was designed so that the model itself can be asked to adjust both meteorological and surface variables. Net radiation, temperature, vapour pressure, and wind speed can be changed in the model itself, while precipitation is altered in its original data set. Site initialization variables are also changeable. These include maximum moisture contents, initial moisture contents, and soil thermal properties. This data set is not altered in the simulations. They were set during model initialization.

To test the sensitivity of the model the following output were analyzed: average surface and soil moisture contents, average surface temperature, thaw date, QH, QE, and Qg. Model sensitivity was tested using 1993 fire weather data.

5.5.3 **Sensitivity to Changes in Net Radiation**

Net radiation was estimated from PAR data and, because this is a crude approximation, its sensitivity in the model needed to be examined. If Q* is wrong, QE may also be wrong. Therefore it is important to determine how much error in Q* is acceptable. If the model is sensitive to the amount of net radiation, errors produced from the estimation technique will be carried through the simulation. If model sensitivity is small, then these errors are reduced in size, and the estimation of Q* using PAR data is acceptable.

Three simulations were performed to determine model sensitivity to net radiation. The first simulation used original data, the soil profile, C1 = 50,000, and C2 = 0.10. The second simulation changed the amount of net radiation to 0.8 of its original values, and the third simulation increased net radiation by 20% (*1.2).

Soil moisture was not noticeably affected by changes to net radiation. Both surface and soil moisture contents experienced change, but only small amounts. Figure 5.8 illustrates change resulting from an increase and decrease in net radiation.

The direction of change was anticipated, but the amount of change was not. A decrease in the amount of net radiation produced an increase in moisture contents as expected, but the increase was only 0.4 percentage points for the surface, and 0.3 percentage points for the soil. When net radiation was increased, similar small changes in moisture contents took place. The surface moisture content decreased 0.3, and soil moisture content decreased by 0.4 percentage points. This indicates a lack of sensitivity to net radiation on moisture conditions. Figures 5.10 and 5.11 show moisture contents reacting almost identically to changes in net radiation.

Changing the amount of net radiation did result in a change in the allocation of energy to the three fluxes. The amount of change was largest in QH. QE had similar amounts of energy in the three simulations, but its percentage of Q* changed substantially (Figure 5.9).

Qg remained stable, both in quantity and percentage. Most change took place to the thermal energy (QH). The increase and decrease in quantity of QH was proportional, but in percentage change Q* = 0.8, was nearly 1.5 times greater than Q* = 1.2. Because the quantity of QE was not affected, moisture contents changed very little. The percentage of QE did change (more for Q* = 0.8), but had a small influence on moisture contents.

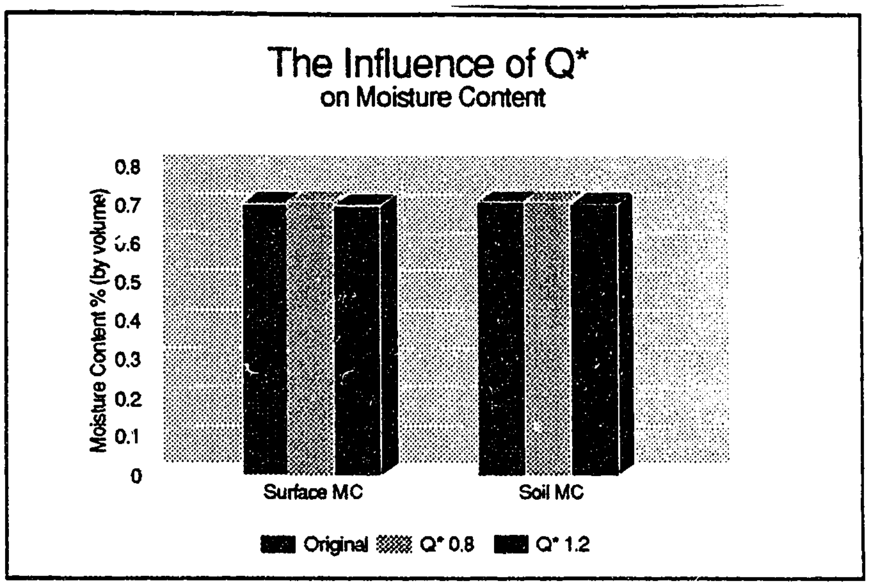


Figure 5.8 Influence of various Q* on moisture contents.

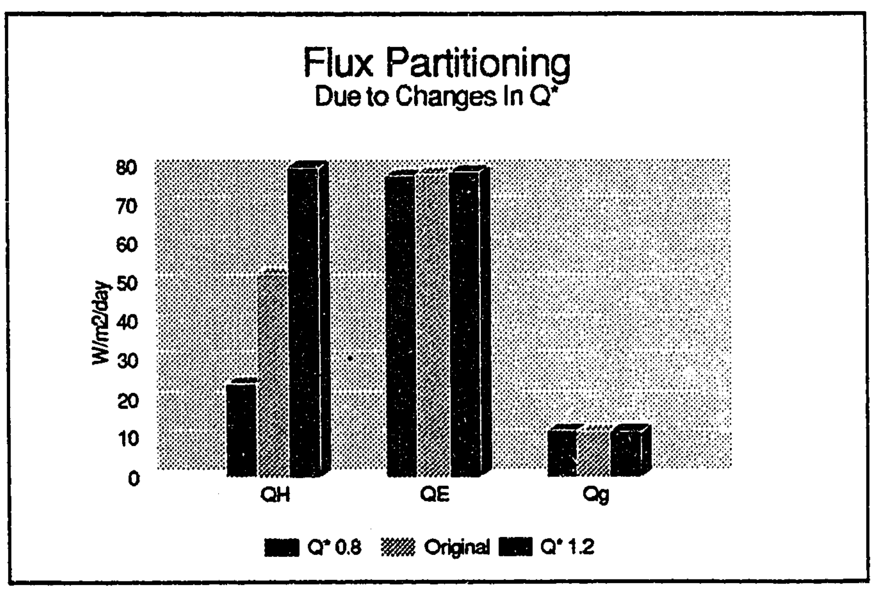


Figure 5.9 Flux partitioning with various Q*.

The large change in the quantity of QH, changed surface temperatures. Q* *1.2 resulted in the average surface temperature increasing 0.18°C. Other than altering temperature in model simulations, this was the largest change in average surface temperatures. Decreasing Q* to 0.8 of its original value, lowered surface temperatures by 0.17°C. The change in QH influenced surface temperatures.

During the three simulations, the quantity of Qg only differed by 0.43 Wm^{-2}, but the timing of the thaw date was influenced. A thaw date of May 23 resulted when Q* = 1.2, and June 2 with Q* = 0.8. This difference is explained by the total amount of radiation energy available at the site. When Q* = .8, only 112.9 Wm^{-2} of net energy existed at the site, while 169.4 Wm^{-2} existed when Q* = 1.2.

For each scenario, a comparison of moisture content was made with the original [data]. Figure 5.8 shows that neither change to net radiation in the model produced a large change from original values. Due to the lack of sensitivity model to changes in Q*, the 'crudeness' of the method estimating Q*, is justified. Results show even if Q* is under/over-estimated by 20%, the resulting influence on evaporation is minimal.

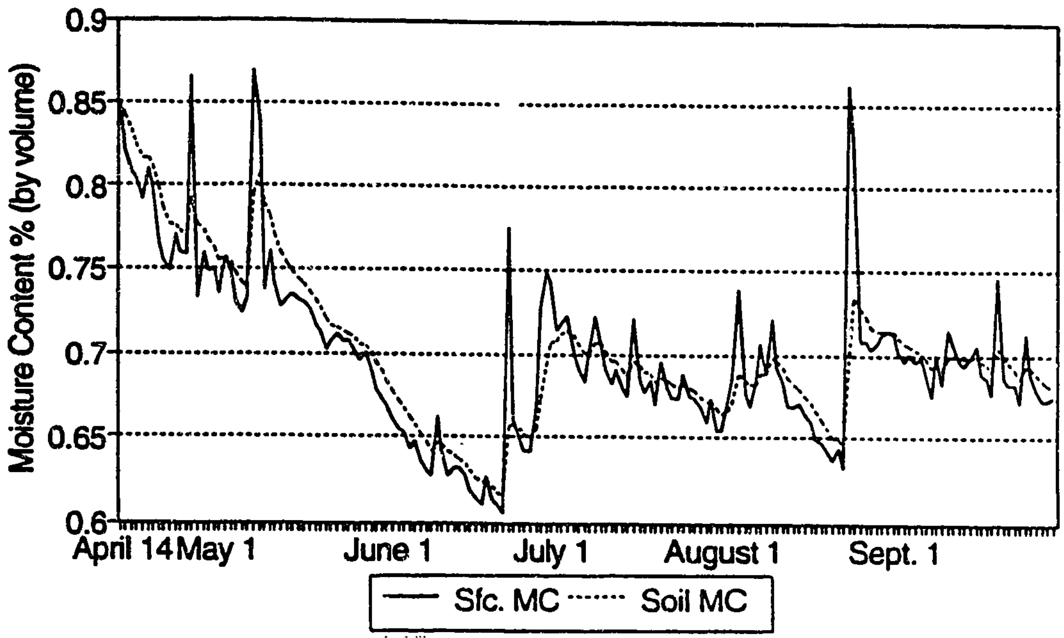


Figure 5.10 Seasonal variability of moisture content to Q* = 1.2

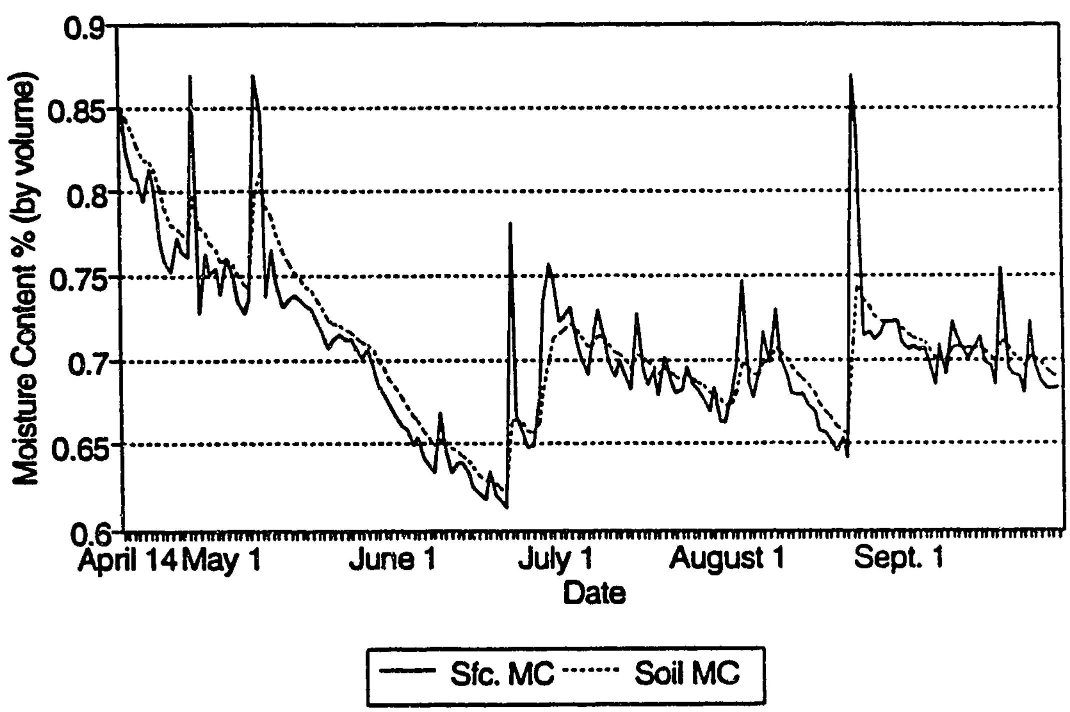


Figure 5.11 Seasonal variability of moisture content to Q* = 0.8.

5.5.4 **Sensitivity to Temperature Change**

The sensitivity of the Halliwell model was tested with changes in temperature of -2.5K, +2.5K, and +4.0K. Results of these simulations are listed in Table 5.3.

Each simulation used the same initialization input, thus total Q* in the simulations are equal. The difference exists in the partitioning of this energy into the three fluxes (QH,QE,Qg) and it has an impact on the moisture conditions calculated for the site.

Table 5.3 Influence of temperature on selected parameters.

	Original Data	T + 2.5K	T - 2.5K	T + 4.0K
Sfc. MC	.703	.654	.755	.622
Soil MC	.707	.658	.759	.627
Sfc. T	16.02	18.47	13.57	19.95
Thaw Date	May 19	May 22	June 11	May 28

Original data produced moisture contents for the surface and soil of 0.703 and 0.707 respectively. Expected changes in moisture conditions occurred with an increase or decrease in temperature. When temperature was increased 2.5K, average moisture conditions decreased 4.9 percentage points. These are similar to the results calculated by the FWI model, and by the CCC GCMII (1986) which predict a decrease in soil moisture of 6.6% with a similar rise in temperature. A decrease in temperature of 2.5K produced an increase in average moisture conditions of 5.2 percentage points (See Figure 5.12).

The partitioning of available energy into the three fluxes was interesting. QE reacted proportionally to the changes in temperature. The 2.5K increase caused QE to rise to 85.7 Wm^{-2} for the season (from 77.9 Wm^{-2} - a 9% increase) leading to a decrease in average moisture conditions. When the temperature was decreased 2.5K, QE dropped to 70.2 Wm^{-2} (a decrease of 9%). This proportional change did not occur with QH or Qg. Instead the change was divided between the two fluxes. When T increased 2.5K, QH decrease 18% to 42.8 Wm^{-2}. When T was decreased 2.5K, QH increased 14% to 60.2 Wm^{-2}. Opposingly with T + 2.5K, Qg increased 11% to 12.7 Wm^{-2}, and with T - 2.5K, Qg decreased 9% to 10.9 Wm^{-2}. With the cooler temperatures, more energy was used to heat the atmosphere, than was used to thaw the ground. The difference in thaw dates between T + 2.5K and T - 2.5K is 20 days.

The division of the three fluxes is illustrated in Figure 5.13. It shows the breakdown of the fluxes by net energy change. The influence of temperature on evaporation is obvious. QE increased by 6 percentage points when the temperature increased 2.5K. A reduction in QH was offset by an increase in Qg which was used to thaw the soil more quickly.

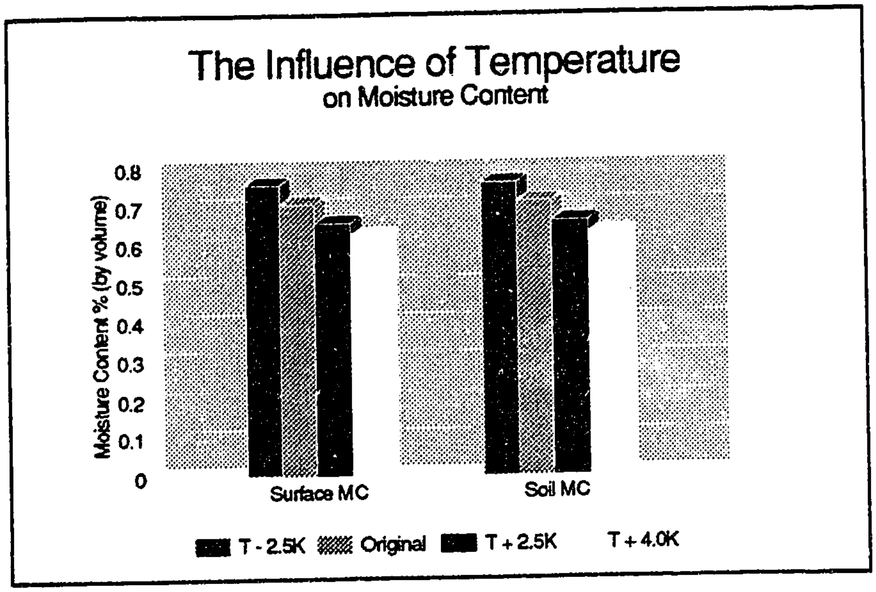


Figure 5.12 Moisture contents with various temperatures.

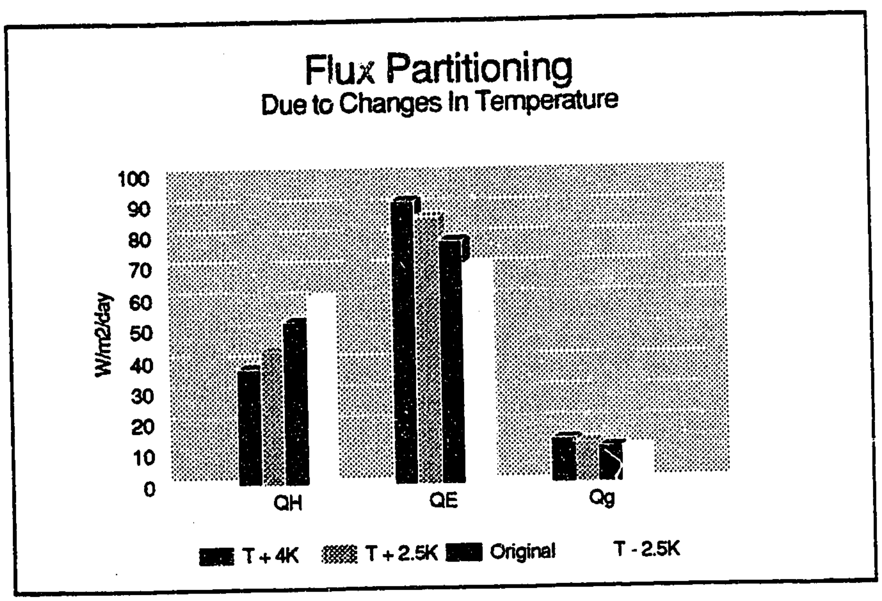


Figure 5.13 Flux partitioning with various temperatures.

Model reaction to the changes in temperature are seen in Figures 5.14 through 5.16. The main feature is the response of the surface to precipitation events. With a decrease in temperature, surface moisture conditions react more abruptly than with warmer temperatures. Surface moisture contents return to near saturation values more readily when the temperature was decreased. They also dried at a slightly slower rate than with increased temperatures. Soil moisture conditions reacted the same way. They increased more rapidly with rain and decreased more slowly when drying. A difference of 15.5 Wm^{-2} (per day) in QE between the two scenarios created this reaction.

When T + 2.5K and T + 4.0K are compared, there is a difference in the response to heavy rain. Moisture contents change more slowly when T is increased 4.0K. This occurs because more evaporation is occurring, especially after rain, and acts to limit the response of moisture values. With lower soil moisture contents, more precipitation is required to reach saturation.

Temperature has an immediate, and increasing effect on moisture content over the fire season. With an increase or decrease in temperature, the impact on moisture content is quick. Soils are wetter or drier than original values, and this difference increases through the season. With increased temperatures, even large amounts of rain, affect moisture contents only marginally.

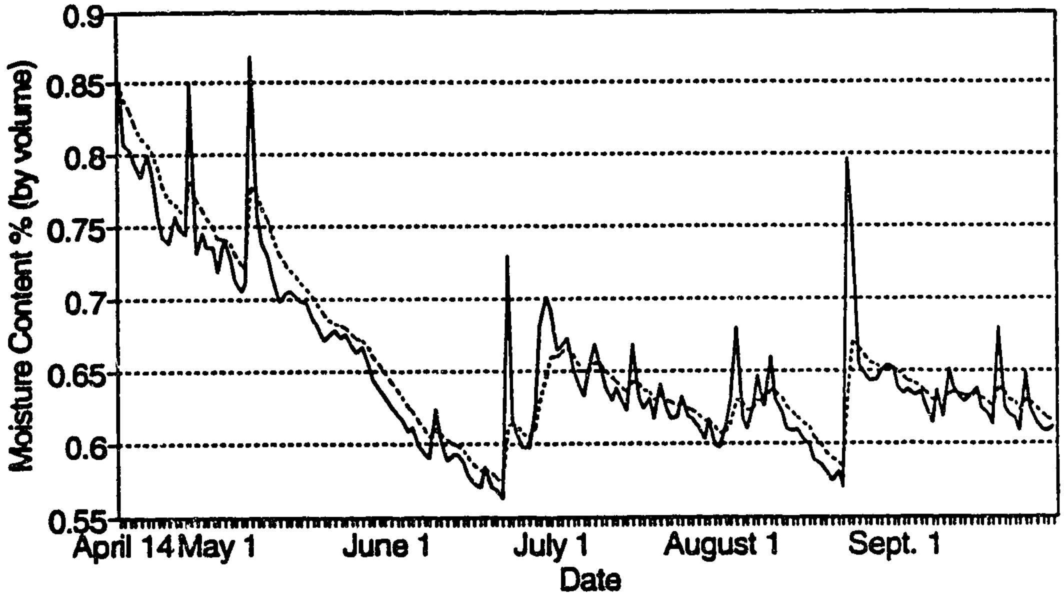


Figure 5.14 Seasonal variability of moisture content to T + 2.5K

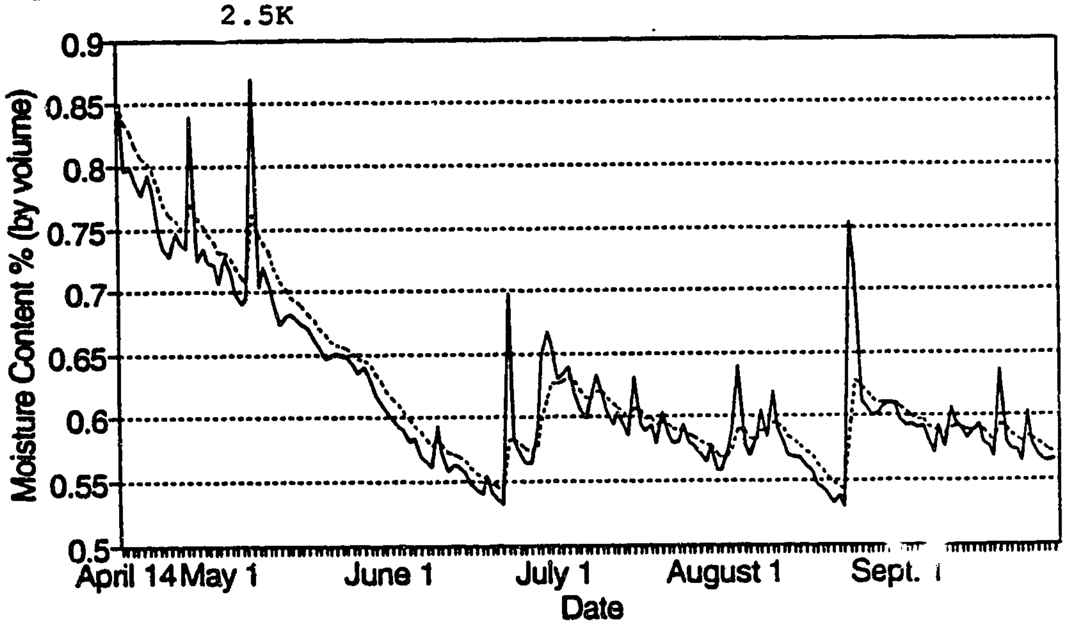


Figure 5.15 Seasonal variability of moisture content to T + 4K

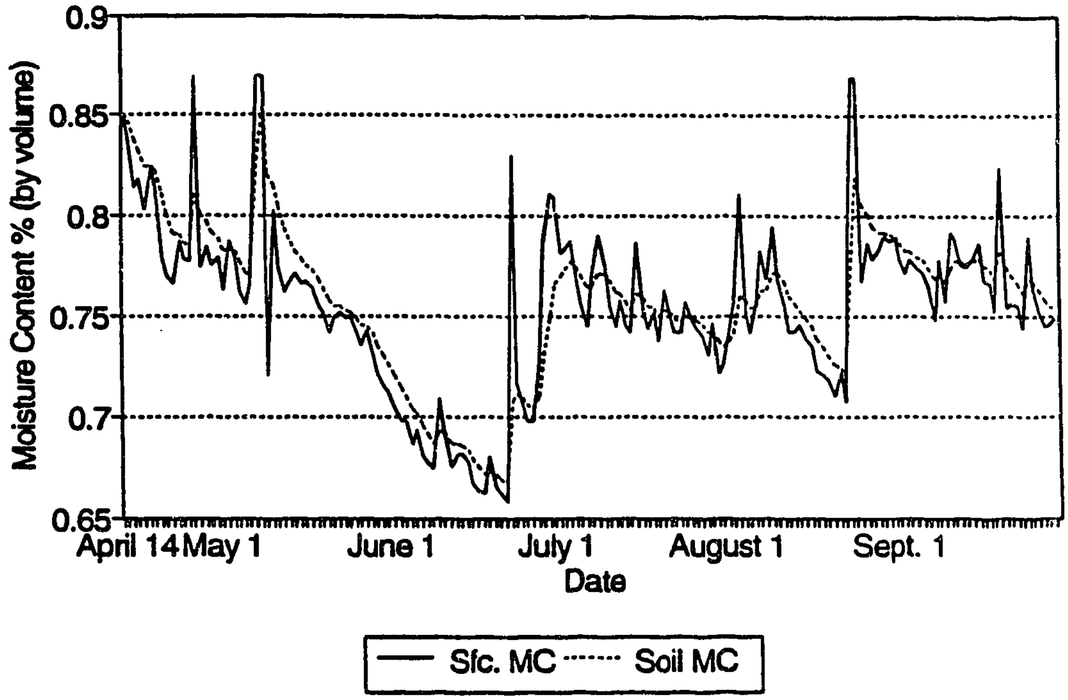


Figure 5.16 Seasonal variability of moisture content to T - 2.5K.

5.5.5 **Sensitivity to Changes in Vapour Pressure**

Vapour pressure in an open atmosphere is defined as that part of the total atmospheric pressure attributable to its water content. As the amount of water vapour molecules increase, so does the vapour pressure, making it difficult for more water molecules to enter the system. Greater amounts of evaporation can increase this pressure and continue until saturation occurs. Vapour pressure depends on temperature and the amount of moisture available on a surface. Highest pressure occurs near the surface and decreases as distance increases from that surface. Lowering vapour pressure would allow more moisture to enter the system, and thus increase evaporation. Vapour pressure can be calculated from relative humidity. When relative humidity was decreased in the FWI model, it allowed more moisture to move from (through) the surface into the atmosphere, thereby lowering surface and soil moisture conditions. The same response is expected in this model, only the changes in the moisture conditions are not yet known. I.P.C.C. (1990), estimates the concentration of water vapour in the atmosphere will increase 20% under a climate change scenario. This would increase vapour pressure at the surface, therefore, it is included as a model sensitivity test.

Figure 5.17 shows the partitioning of energy into the three fluxes with sensitivity tests that decrease vapour pressure to 0.8 the original value, and increase vapour pressure by 1.2 times the original.

Evaporation (QE) is greatly influenced by a change in vapour pressure - far more than a change in net radiation produced, and similar to the change in QE produced from altering temperatures. In these simulations, change is restricted to two fluxes; QH and QE, and is split between the two. Qg is not affected by a change in vapour pressure.

When atmospheric vapour pressure is decreased it creates a stronger humidity gradient which draws water away from the surface and soil and decreases moisture contents. Figure 5.17 shows an increase in QE when the vapour pressure is lowered. QE increases its partitioning by 4 percentage points with a decrease in vapour pressure. Conversely, when vapour pressure is increased QE decreases by 4 percentage points.

Moisture contents of the surface and soil reflect the increases and decreases of QE. Figure 5.18 shows the changes in soil moisture resulting from altered vapour pressures.

Surface and soil moisture contents decrease 3.7 percentage points when vapour pressure is 0.8 of its original value. These increase when vapour pressure is increased 20%. Surface and soil moisture contents increase 4.2 percentage points. Moisture contents are more sensitive to increases in vapour pressure. This can be seen in Figures 5.19 and 5.20. Moisture contents react dramatically to rainfall events when there is an increase in vapour pressure. Increases or decreases in moisture contents occur at a consistent rate during the season. Model response is quick - it returns to surface saturation values more readily, with the equal amounts of precipitation, than do other sensitivity tests. Increasing vapour pressure allows more moisture to be held in the atmosphere, but restricts entry. Using cycling coefficients C1 = 50,000, and C2 = 0.1, the greater amount of moisture in the atmosphere acts to increase model sensitivity.

Because the percentage of Qg does not change in these simulations, the thaw date remains almost the same. Only a two day difference exists between the two tests. Average surface temperature are constant - only a difference of 0.07°C exists between the two tests, and is not a large change from the original temperature of 16.02°C.

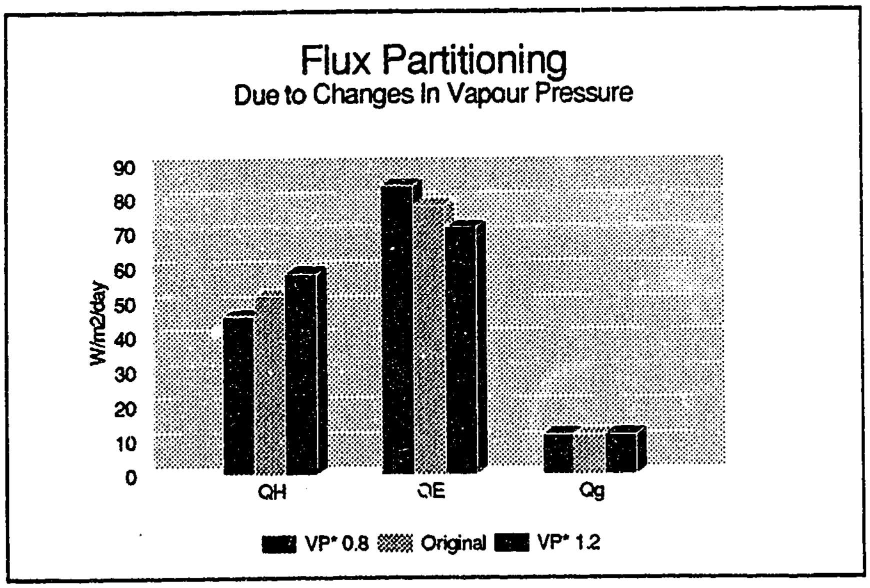
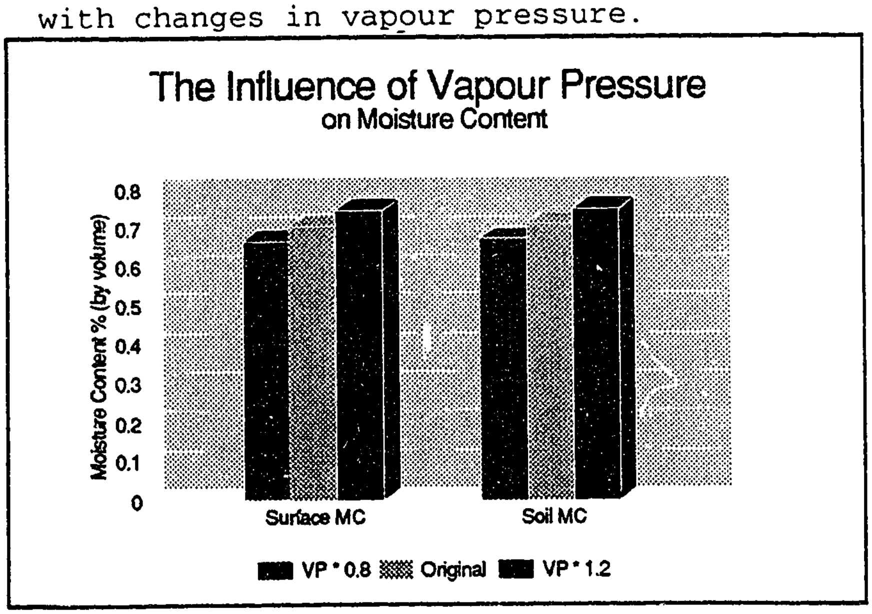


Figure 5.17 and 5.18 Flux partitioning and moisture content with changes in vapour pressure.



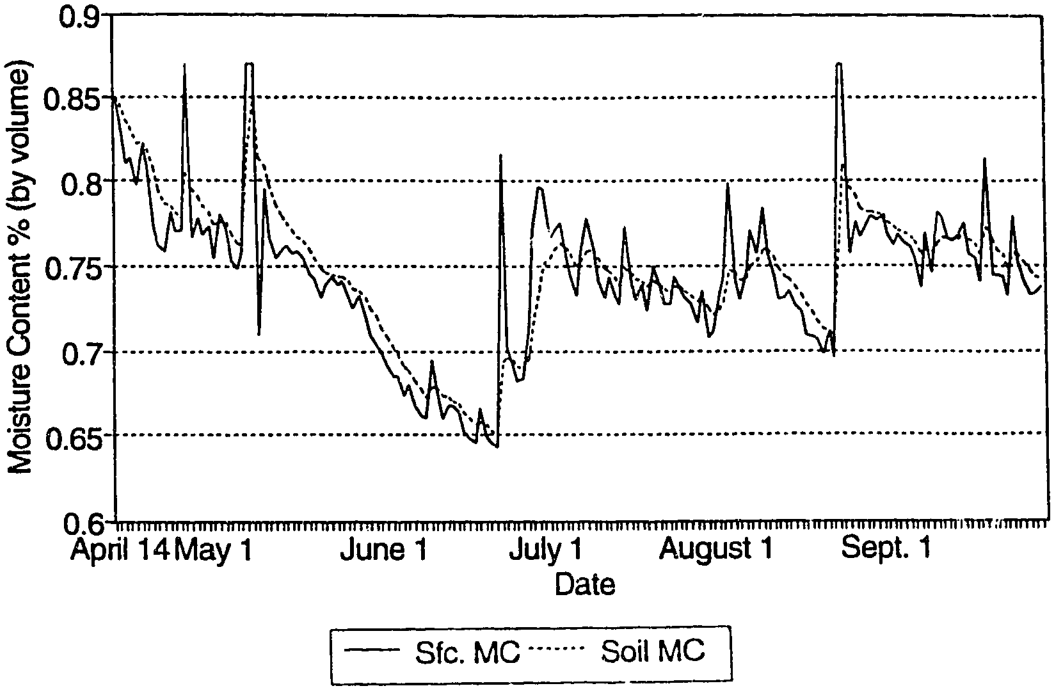


Figure 5.19 Seasonal variability of moisture content to VP * 1.2.

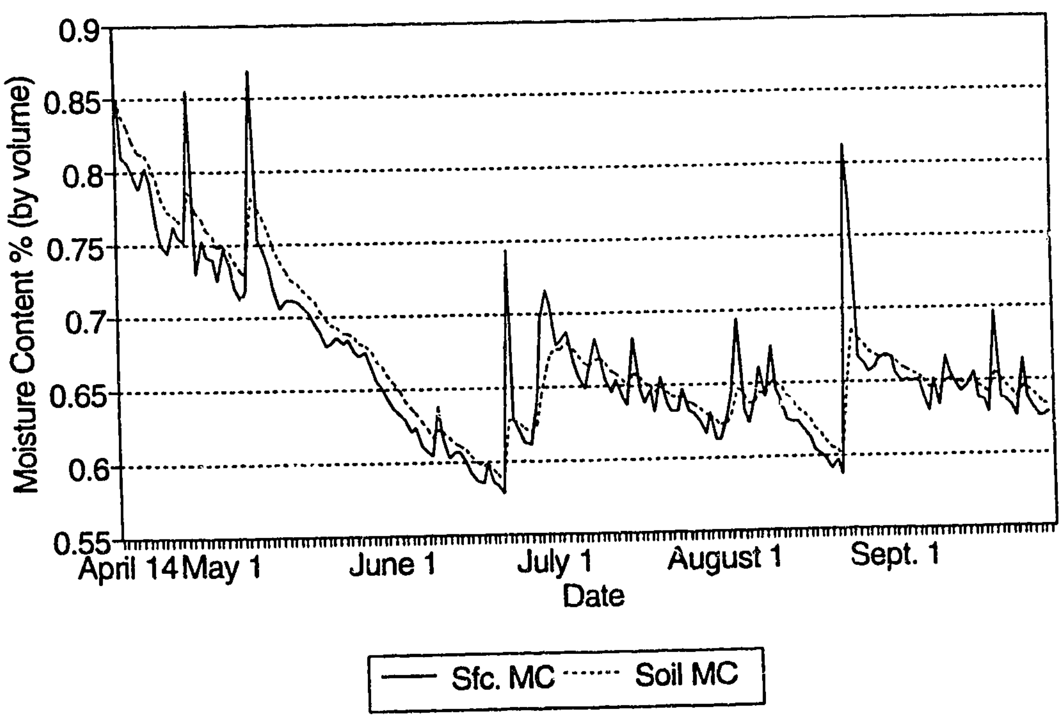


Figure 5.20 Seasonal variability of moisture content to VP * 0.8.

5.5.6 **Sensitivity to Changes in Wind Speed**

Changing windspeed had a minimal effect on resulting moisture contents. In fact, the change in moisture contents averaged only 0.15 percentage points. Two simulations were run in the Halliwell model to test its sensitivity to changes in wind speed. The first simulation increased windspeed by a factor of 1.25, and the second decreased wind speed by one-half. Figure 5.21 shows the response of moisture contents to these changes, and they are almost identical. No visible differences exist. Figure 5.22 identifies the very small changes in the three fluxes to changes in wind speed.

0.47 Wm^{-2}, 0.19 Wm^{-2}, and 0.31 Wm^{-2}. These are the differences between the largest and smallest values for QH, QE, and Qg, respectively. They are not large enough to produce a change in the percentage each flux contributes to the net energy. Consequently, moisture contents change by very small amounts, if at all.

Changes in moisture contents are minor, even with large changes in windspeed. Wind speed can approach 0 m/s near the surface, a moderate distance into a forest. These results may be realistic; that wind speed has a minor effect on forest fuels within a forest, but it was expected that the model would be more sensitive, especially the surface moisture contents.

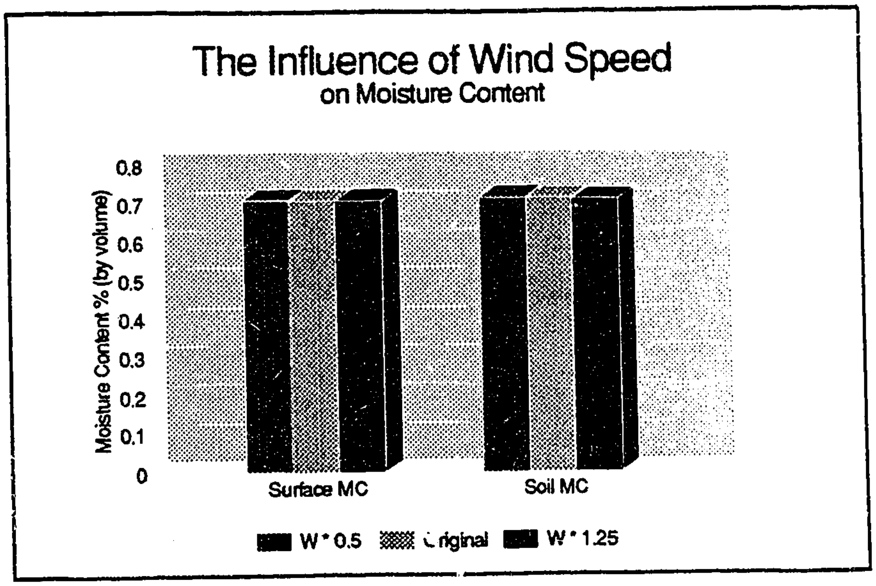


Figure 5.21 Moisture contents with various wind speeds.

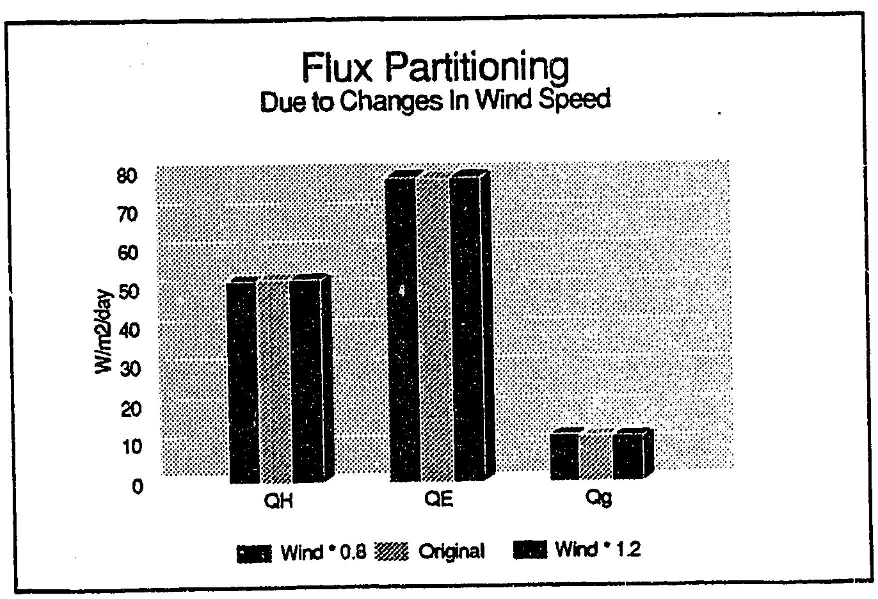


Figure 5.22 Flux partitioning with changes in wind speed.

One coefficient in the model (Z_o), may be responsible for the minor effect of wind on moisture contents. The bulk effectiveness of the forest community as a momentum absorber is described by Z_o. Z_o is the surface roughness height and is related to the height of the surrounding vegetation. In coniferous forests this value ranges between 1 and 6, and is roughly determined as $Z_o = .13h$ (Monteith Vol.2, 1975), where h is the height of the trees. In the model $Z_o = 1.3$ m, and this value is adjustable. The Halliwell model uses a very crude estimate of aerodynamic resistance within the canopy. It is based on windspeed (u) above the canopy, and surface roughness. The results of these simulations were similar to original model output. Change in moisture contents were only 0.15 percentage points. Large changes in the aerodynamic resistance and (u) is not a problem; this technique, even if flawed, does not have a large sensitivity. Figure 5.21 supports the use of the log wind profile. Because there was a lack of sensitivity from the model to changes in wind speed the large changes had little effect on resulting moisture contents. Errors in the model produced by the chosen wind profile will not be carried through, or decrease the ability of the model to produce evaporation rates. Any error produced will be very small and the influence on results minimal.

Changes in average surface temperatures were recorded. A wind speed of one-half the original values increased average surface temperature from 16.02°C to 16.34°C. This is the largest change in surface temperature that occurred (not including actual changes to temperature), and is significant, but did not influence evaporation. Decreasing windspeed by one-half lessened the effect of the transference of energy away from the surface - but did not increase moisture contents on the surface by more than 0.2 percentage points. Increasing wind speed by 1.25 times decreased the average surface temperature by only .06°C. This is below the rate of change that decreasing windspeed had.

Thaw dates were almost identical for the two sensitivity tests. A one day difference between the two simulations existed. Decreasing wind produced one extra day of frost in the ground.

Changes in windspeed (u) leads to changes in r_a, but similarly effects QH and QE. As a result QH/QE=β (Bowen Ratio) does not change much, and produces only a slight shift from (QH and QE) to (Qg).

5.5.7 Sensitivity to Change in Precipitation Amounts.

Changing the amount of precipitation within the model led to large changes in the allocation of available energy. By increasing precipitation there is more moisture available for evaporation. QE should increase in this scenario. Very high rates of evaporation follow precipitation. In contrast, with less moisture available to the system, QE should decrease in net amount and partitioning (%). C1 and C2 were initialized using the original data. During initialization, C1 reacted sharply to major precipitation events.

Modifications were made to alleviate this problem and to account for increased surface drying following rain. The model then appears to work more accurately. With an increase in precipitation, this problem returned, but to a lesser extent.

Moisture contents increased substantially with an increase in precipitation, but the model reacts by drying to unrealistic values following these rainfalls. The drying was less dramatic than what occurred using original values for C1 and C2, but still manifested itself, specifically with two rainfall events. Figure 5.24 shows that in early May and late August, after rains of >30 mm, the surface layer experienced major drying in the P * 1.25 scenario. Because the surface is more responsive when C1 = 50,000 s/m, the surface returned to higher moisture contents more frequently than the scenario where P * 0.8. Drying was faster with less rain, and average moisture contents were 3.8 percentage points lower for the season. There was a 180 mm difference in rainfall between the two scenarios.

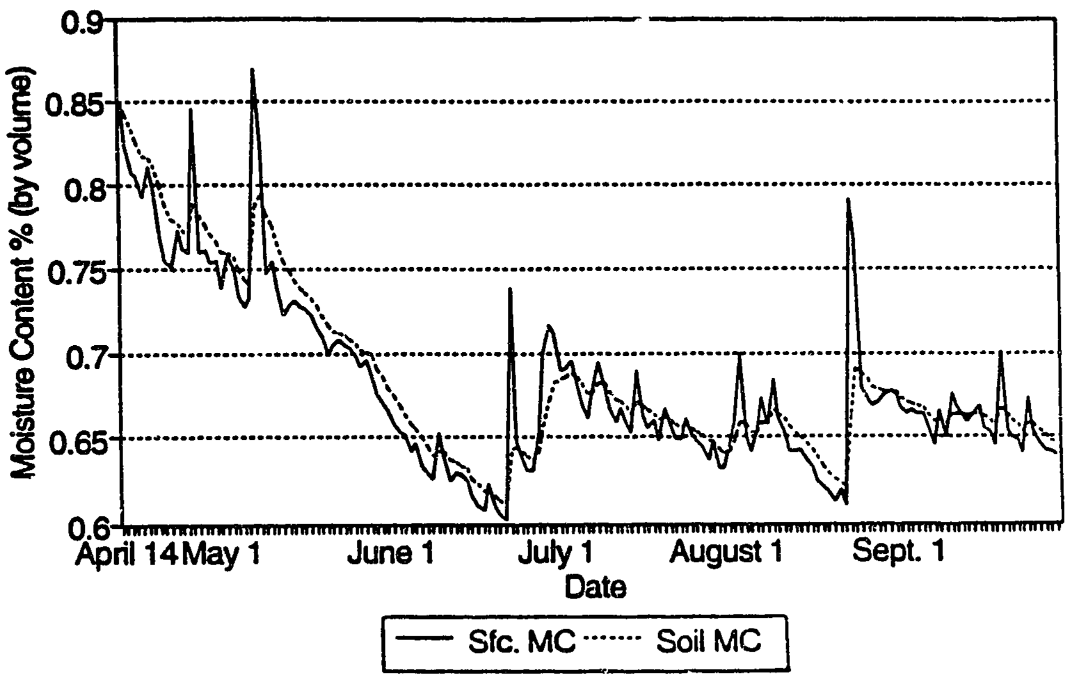


Figure 5.23 Moisture contents with a decrease in precipitation.

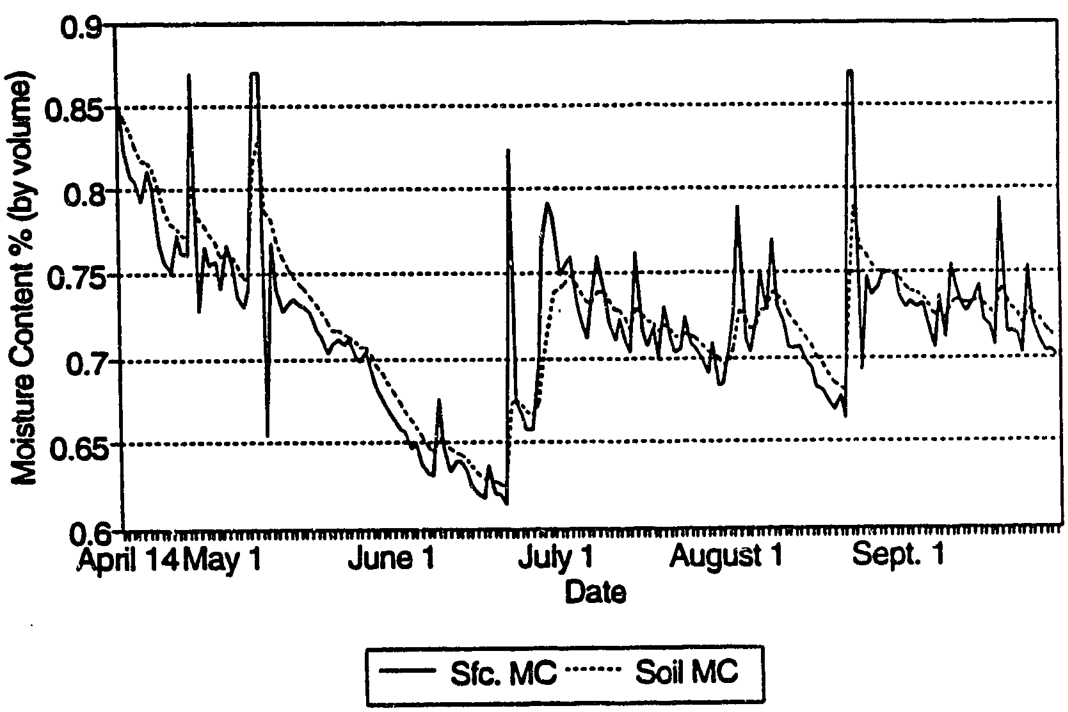


Figure 5.24 Moisture contents with an increase in precipitation.

With an increase in precipitation (P*1.25), 500 mm of precipitation was introduced to the system. Of this, 493 mm evaporated. When precipitation was decreased (P*0.8), 320 mm of rain fell and 386 mm evaporated (higher QH). A difference of 100 mm in evaporation resulted in moisture contents 4 percentage points lower for the season. 422 mm of evaporation occurred using original data. Figures 5.25 and 5.26 summarize the response of the model to changes in precipitation amounts.

Qg did not change its partitioning under either scenario. Changes affected QH and QE only. The change in QH was substantial. Less precipitation meant more energy was available to QH, leading to a higher surface temperature (16.07°C). Less precipitation led to a 10% decrease in evaporation (QE), but only a 5% change in its partitioning. The other 5% was transferred to QH, which was 13 percentage points greater than in the original simulation. QE increased 13 percentage points with greater rainfall, and 8% in its percentage of the net energy in the system. QH decreased 23 percentage points with greater amounts of rain. This increase led to high rates of evaporation. Greater evaporation modified the increase in moisture contents, as values increased only 4 percentage points.

Thaw dates were influenced by changes in precipitation. With greater rainfall, frost left the ground 7 days sooner than when precipitation was decreased.

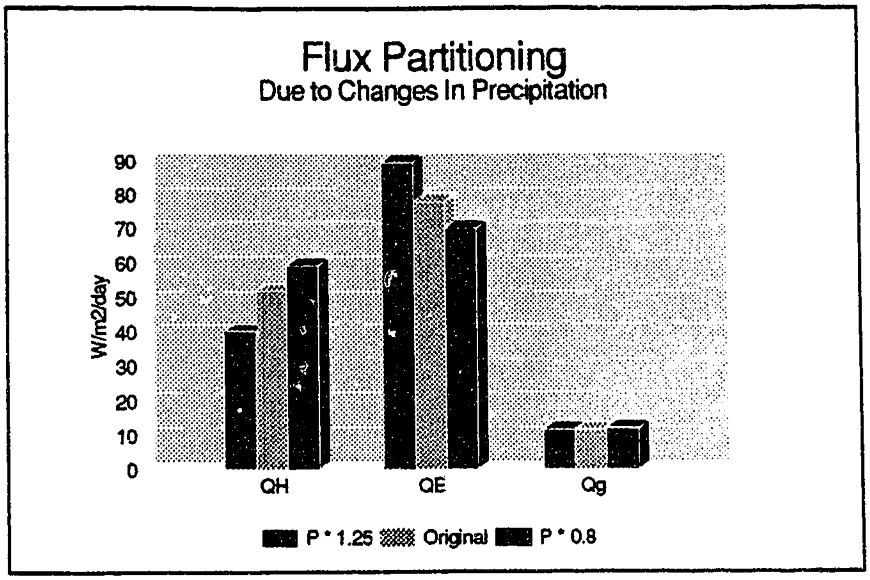


Figure 5.25 Flux partitioning with changes in precipitation amounts.

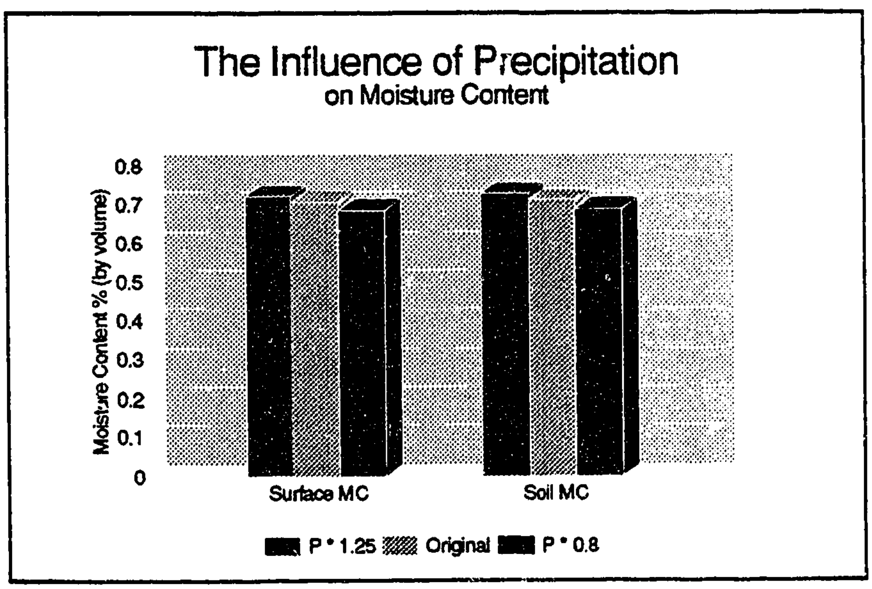


Figure 5.26 Moisture contents with various amounts of precipitation.

Figure 5.27 is a summary of the sensitivity of the Halliwell model to the changes used above. This figure shows the importance of each climatic variable, and thus its influence on fire danger. Model sensitivity is as follows (in order of influence on evaporation): temperature, vapour pressure and precipitation, Q*, and windspeed.

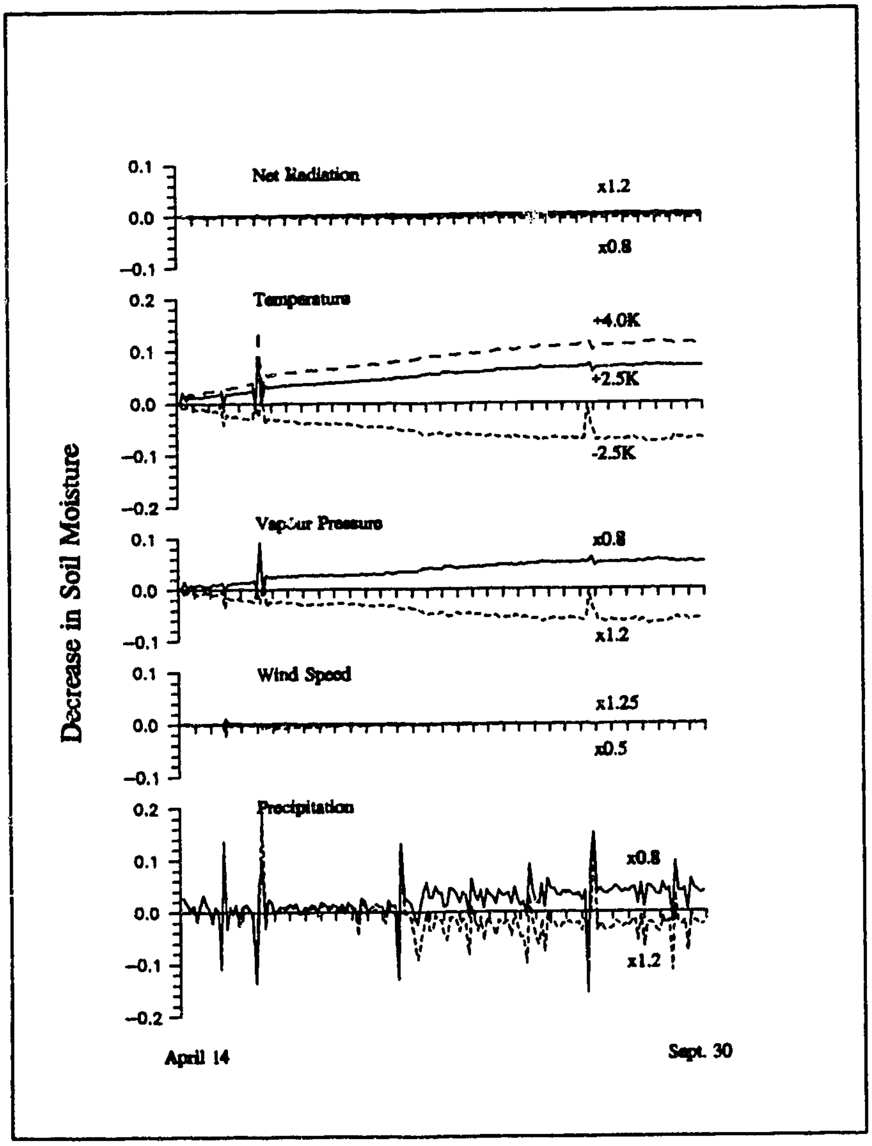


Figure 5.27 Sensitivity of individual variables to change.

5.5.8 **Sensitivity Tests Changing Combinations of Variables**

The Halliwell model was developed to allow variables to be changed in combination. Using selected climatic variables, sensitivity tests found temperature, vapour pressure and precipitation, in that order, to be the most important variables in determining moisture contents. Wind had almost no effect on moisture contents. Q^* had very little effect, even with large changes. The FWI model produced similar results. Temperature and precipitation were found to be the most important variables affecting fire danger.

Two sensitivity tests were run with changes to two variables. The first test altered temperature and precipitation, while the second altered temperature and vapour pressure. The results of both sensitivity tests are shown in Table 5.4.

Individually, a temperature increase of 2.5K, reduced average moisture contents 4.9 percentage points, and a precipitation increase of 1.25 times, increased moisture contents 1.75 percentage points. In the scenario combining the two variables, moisture contents decreased 2.5 percentage points, to a volumetric moisture content of 0.68. The increase in temperature and precipitation created the highest rate of evaporation of any sensitivity test performed. QE recorded a seasonal mean value of 96.1 Wm^{-2}.

This scenario may be similar to that expected with climate change. If temperatures increase, even with greater amounts of precipitation, the model reflects a net drying of the surface and soils, due to higher rates of evaporation. 528 mm of evaporation occurred in this scenario, with 500 mm of precipitation - resulting in a net drying.

With high evaporation rates (and with net radiation remaining constant) the other fluxes also experienced change. QE made up 68% of the total net energy within the system in this scenario. QH experienced a large decrease in both total amount of energy and the percentage of energy it contributed. Other than the scenario where Q* was decreased, QH had its lowest value. Only 32.4 Wm^{-2} of energy was allocated to QH, only 23% of the total net energy in the system (compared to 37% using original data).

Table 5.4 Influence of changing two variables on selected parameters

Scenario	Original	T + 2.5K & P *1.25	T + 2.5K & VP *0.8
Sfc. MC	.703	.678	.618
Soil MC	.707	.682	.623
Sfc. T	16.02	18.41	18.45
Thaw Date	May 19	May 22	May 22
QH (Wm^{-2})	51.9	32.4	37.3
QE	77.9	96.1	91.2
Qg	11.3	12.6	12.7

Qg increased slightly, but continued to make up 8% of the energy. Thaw date was consistent with the two sensitivity tests describing the individual changes in temperature (T +

2.5K), and precipitation (P *1.25). Thaw date was May 22.

Figure 5.28 shows the seasonal patterns for surface and soil moisture contents for this scenario. Two points are noticeable; first, following periods of little precipitation, moisture contents are 5 percentage points lower than the original. Faster drying results from the higher temperatures. These values are slightly higher than the scenario where temperature was increased individually. The second feature is that during rainfall, moisture contents move from values 5 percentage points lower than those of the original test, to being equal to them. With greater amounts of precipitation, moisture contents return to higher levels than when temperature was increased individually. These values are 5 percentage points higher than those in the T + 2.5K scenario. The model reacted by drying to unrealistic levels after a rainfall event only once (late April). This type of reaction only occurs when rainfall is altered (increased). The increase in temperature combined with increased precipitation modifies this type of drying in the model.

Results of the second sensitivity test are listed in Table 5.3. This scenario consisted of increasing temperature 2.5K, and reducing vapour pressure to 0.8 times its original value. The scenario produced the lowest moisture contents of any scenario using the 1993 data.

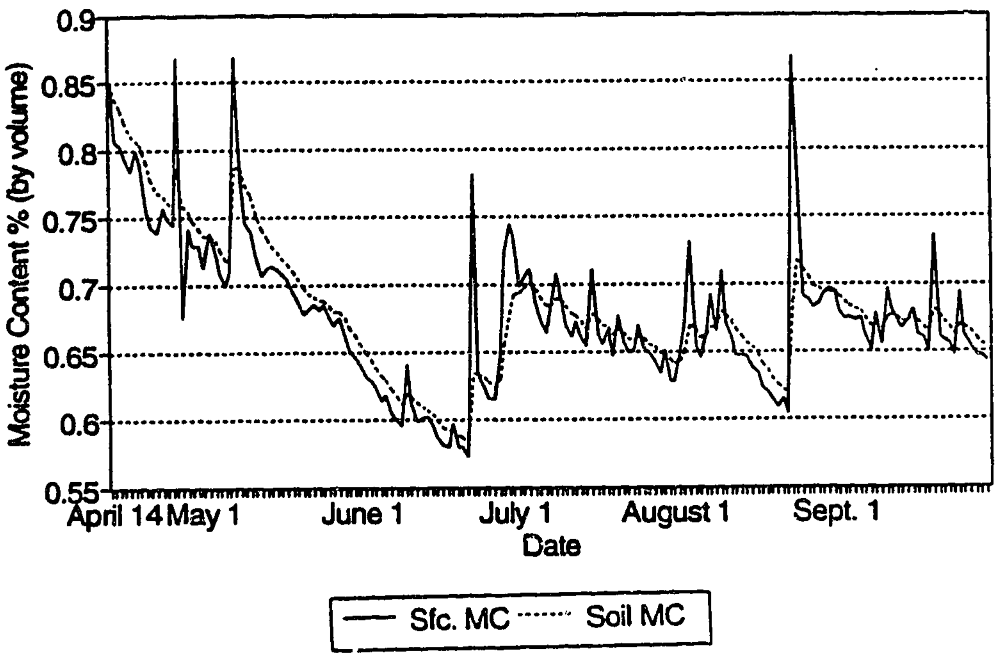


Figure 5.28 Seasonal moisture contents with T + 2.5K and P * 1.25.

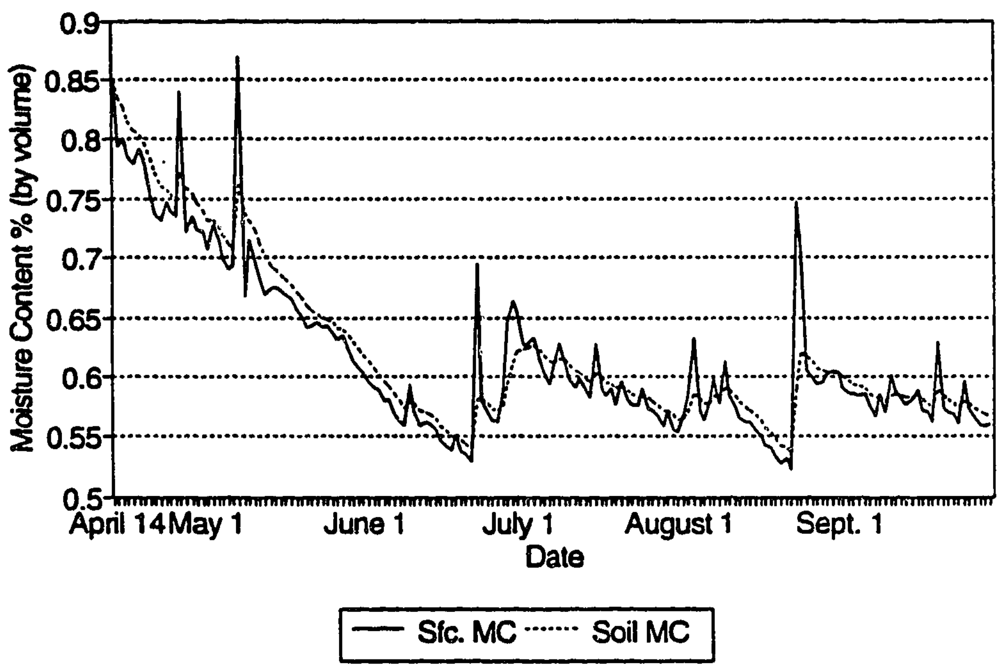


Figure 5.29 Seasonal moisture contents with T + 2.5K and VP * 0.8.

Individually, increasing temperature 2.5K, lowered moisture contents 4.9 percentage points, and a decrease in vapour pressure lowered moisture contents 3.7 percentage points. When the two were combined moisture contents decreased by 8.5. Evaporation rates are lower than when precipitation was increased, but are still significant. QE averaged 91.2 Wm^{-2} for the season, the second highest value produced. This equals 501 mm of evaporation for the season. Figure 5.29 show these values, and with these low moisture contents, heavy precipitation events are not able to raise moisture contents to levels equal to other scenarios. Saturation was only reached once, and moisture contents after heavy rain were still 8-9 percentage points lower than the values reached in the original simulation. The relative ease at which moisture was able to move across the surface boundary (C1) in this scenario was responsible for the low moisture contents.

5.5.9 Sensitivity Test with Changes to Three Variables

One sensitivity test was performed altering three variables. This test may simulate a realistic climate change scenario. It uses the T + 2.5K, P*1.25 scenario above, and combines a change in vapour pressure. With an increase in precipitation, vapour pressure should increase, producing more water molecules in the atmosphere immediately above the surface. Vapour pressure was increased 1.2 times the original data. Table 5.5 lists the results of this sensitivity test, comparing the results to the scenario above and to the individual increase in vapour pressure.

Moisture contents are remarkably similar to those of the original simulation. In fact, the moisture contents have increased 0.3 percentage points for the season. Individually, increasing vapour pressure decreased evaporation by 35 mm from the original data. The T +2.5K, and P*1.25 scenario had 100 mm more evaporation.

Table 5.5 Various scenarios influence on selected parameters.

Scenario	T+2.5K, P*1.25 VP*1.2	T+2.5K P*1.25	VP*1.2
Sfc. MC	.706	.678	.745
Soil MC	.710	.682	.749
Sfc. T	18.45	18.41	16.06
Thaw Date	May 22	May 22	May 23
QH (Wm^{-2})	36.9	32.4	58.3
QE	91.5	96.2	71.4
QG	12.7	12.7	11.5

The scenario produced a total of 503 mm of evaporation, and 500 mm of precipitation. As a result, moisture contents were close to original values. Increasing vapour pressure has a very strong influence on resulting moisture contents (See Figure 5.30).

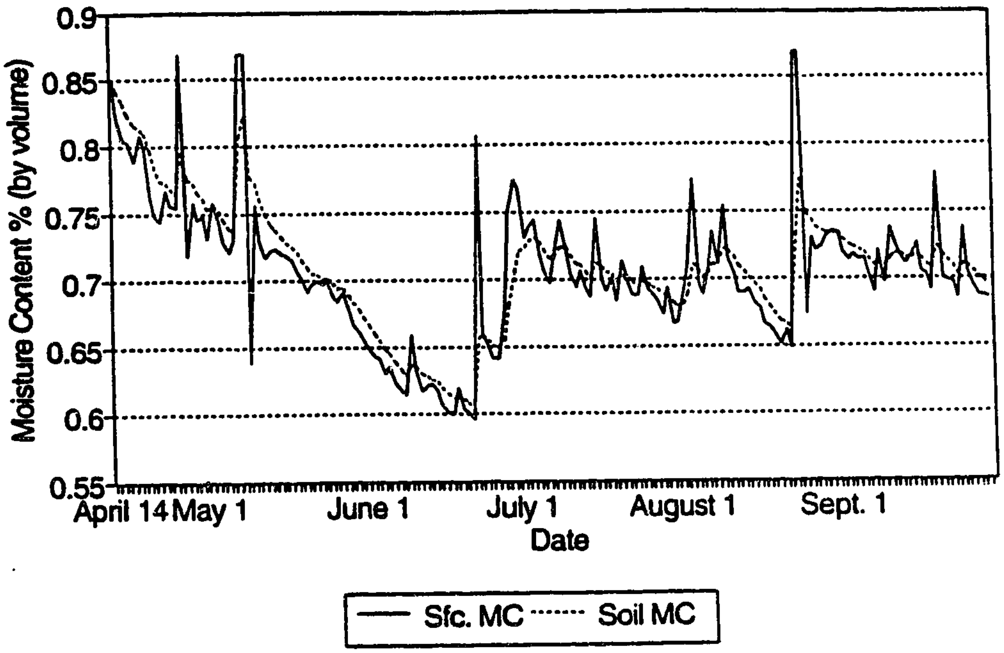


Figure 5.30 Seasonal moisture contents with T + 2.5K, P * 1.25, and VP * 1.2

5.6 **CCC GCMII scenarios**

Because cloud data was not available for the period before 1987, only two climate change scenarios were run for the same years selected for use in the FWI model (1993 and 1988). Other years were selected for study. The selected years represent various levels of fire danger, and are used to illustrate as many potential changes due to climate change as possible. These years were subjected to the same climate change scenario produced by CCC GCMII and used in the FWI model.

For the same rationale used in the FWI simulations, vapour pressure and wind speed are not altered. PAR data was estimated for all years other than 1993, and cloud data was synthesized for the 1977 scenario. The cloud data set was manufactured based on daily weather records, and the distribution of cloud type days, based on frequency using cloud data from 1988 to 1993. Days with precipitation > 5 mm were overcast; 1-5 mm, either scattered or broken (depending on the previous day), and clear days were those that did not have any precipitation within three days. The number of days in each category were similar to the frequency distribution produced from the period 1988 - 1993.

5.6.1 **1993 CCC GCMII Scenario**

The first sensitivity test using climate change output from CCC GCMII was run with 1993 fire weather data. 1993 was categorized a cool/wet fire season. It experienced the highest daily average QE in W/m^2, of the selected study years (77.9 Wm^{-2}) for the fire season. High evaporation rates combined with cool temperatures, thereby maintaining high moisture contents for most of the season.

The majority of rainfall occurred during the June-August period during the 1993 fire season. CCC GCMII output predicts less precipitation during this part of the summer, and, as a result, actual precipitation in the simulation decreased (although minimally).

Results of the climate change scenario are listed in

Table 5.6. This table compares original 1993 data to those produced by the climate change scenario.

The climate change scenario produced a decrease in surface and soil moisture contents for the season. A 3.1 percentage point decrease occurred with approximately the same amount of precipitation. Climate change scenarios produced in the FWI model found temperature to have the largest influence on moisture contents. Lac La Biche usually receives minimal precipitation during April and May. Seasonal precipitation characteristics may imply that the temperature change will dictate the severity of fire danger.

Table 5.6 1993 CCC GCMII Scenario.

Scenario	1993 Original Data	1993 CCC GCMII
Sfc. MC	.703	.672
Soil MC	.707	.676
Avg. Sfc. T	16.02	19.73
Thaw Date	May 19	May 12
QH (Wm^{-2})	52.0 (37%)	41.9 (30%)
QE	77.9 (55%)	85.8 (61%)
Qg	11.4 (8%)	13.5 (9%)

A sensitivity test with a 4°C increase in average temperatures was run. It produced an average surface temperature of 19.95°C. This is only 0.22°C higher than the results of the CCC GCMII scenario, but moisture contents were dissimilar. The T + 4.0K sensitivity test had seasonal moisture contents that averaged 0.624. The CCC GCMII scenario produced average moisture contents of 0.674 - a difference of 5 percentage points. Average temperatures in this scenario increased 3.8°C. An increase of 4K produced 86.4 MJm^{-2} more seasonal evaporation (QE), an average of 91 Wm^{-2}.

An average increase of 5 Wm^{-2} in evaporation caused a difference of 5 percentage points in average moisture conditions for the site. With precipitation and temperature changes the relationship between the original 1993 data and the climate change scenario is more complex.

The CCC GCMII scenario increased daily evaporation rates by 8 Wm^{-2}. But moisture contents differed only 3.1 percentage points. The largest difference in moisture contents resulted after one month of relatively dry weather (mid-May to mid-June). At the end of this period moisture contents had decreased an additional 4.5 percentage points. This is similar to that found in the FWI model. Extended periods of dry weather, under a changed scenario, will result in moisture contents that are much drier than under present weather conditions. Since more evaporation occurs with climate change conditions, model response to precipitation is modified. Higher temperatures and greater amounts of evaporation follow a rainfall. This allows fuels to return to equilibrium moisture contents more quickly than under present climatic conditions.

During periods of high fire danger (estimated by the

FWI model), evaporation rates (QE), drop to low levels. A comparison of periods defined as high danger (FFMC's greater than 88.5), and the modeled evaporation rates for the same time period, was made. 1993 produced very few days of high danger. Only one extended dry period took place during the season (see Figure 5.31) and during this period only one stretch of 10 days had FWI indices in the high danger range, May 31 to June 9. FFMC's were in the high 80's, and only twice reached a value of 90. Moisture contents declined during this time (Figure 5.32). With high seasonal precipitation, QE maintained relatively high values, but during the stretch of high danger, QE declined to seasonally low values. A 3 day period had danger levels that approached extreme (June 2-4). This is illustrated in Figure 5.31, where QE declined to values near 25 Wm^{-2}. Because 1993 was so wet, it is difficult to establish a relationship between QE and fire danger. Other seasons may provide better examples.

High danger periods can be identified by the duration of time QE has low values. During early June (Fig.5.31), QE values remain low for an extended period of time. This differs from other periods (of similar low values) because of the length of time. Low values of short duration may be in part due to the model's response to precipitation. Increased QE values followed by sharp declines may be the models oversensitive response to rainfall.

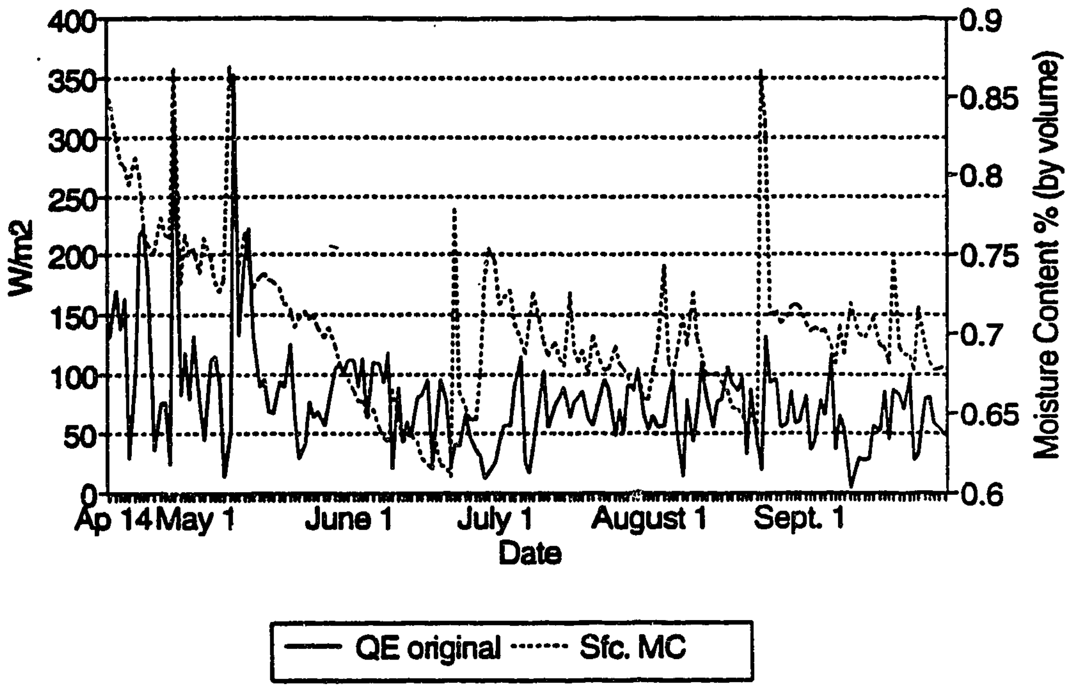


Figure 5.31 A comparison of moisture contents and QE values.

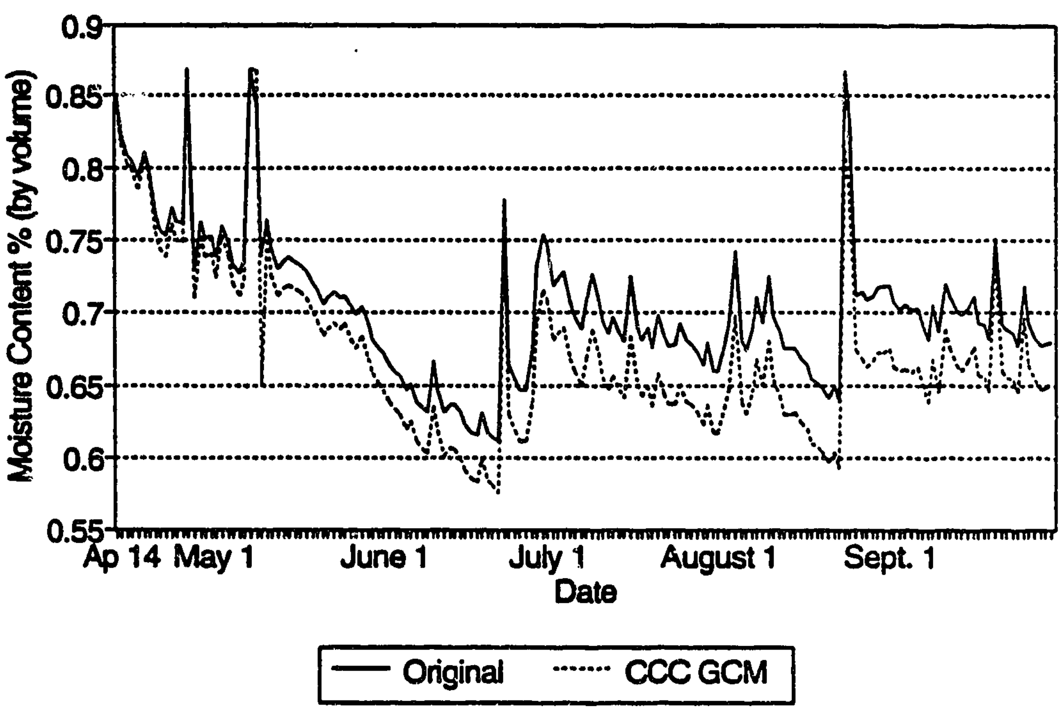


Figure 5.32 Surface moisture contents from original and CCC GCM simulations.

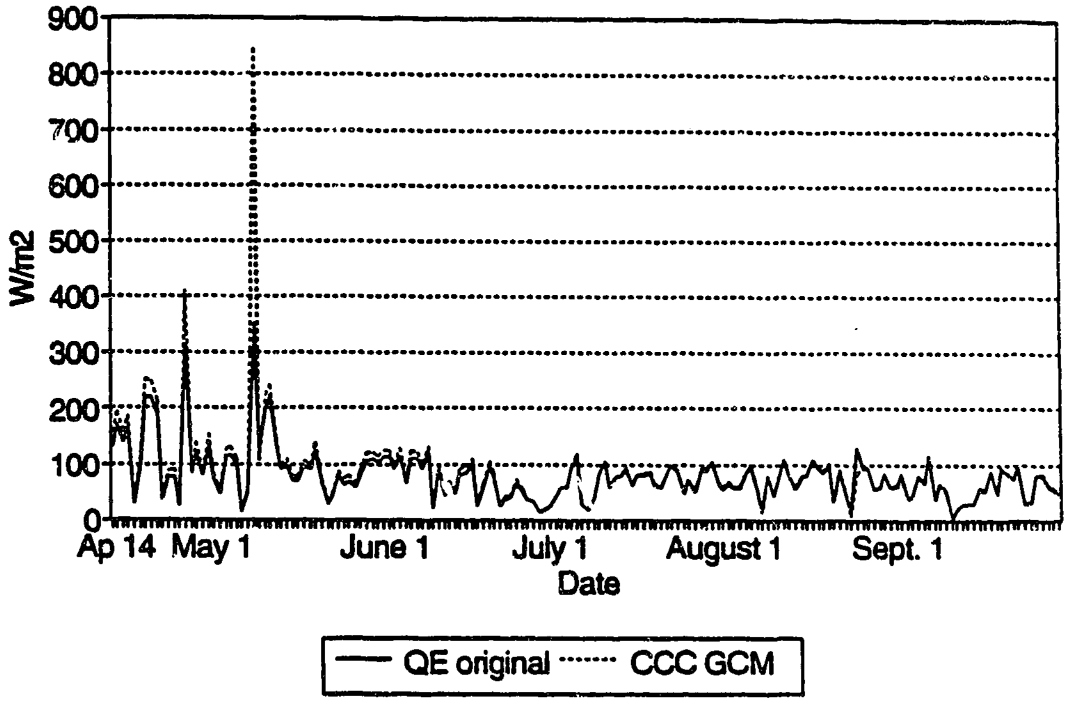


Figure 5.33 Daily QE values from original and CCC GCM simulations.

Figure 5.33 is a comparison of QE using original 1993 data and the climate change scenario. The CCC GCM scenario produced more evaporation than the original data. Most of this difference occurred in the months of April, May and June. Warmer temperatures and more precipitation combined to produce higher values. Because precipitation was abundant during summer months, little difference existed in QE over this period. The CCC simulation produced slightly higher evaporation rates during this time leading to an increased fire danger in the spring season, but there was not a significant difference.

Climate change produced only a limited change in fire danger. Only during the dry period, did danger levels rise to values that may require attention from the forest service. During this time moisture contents were 5 percentage points lower than those from the original data. The abundant precipitation during the fire season did not allow the difference in surface moisture contents to increase through the summer (Figure 5.32). Other scenarios reveal that as the season progresses, the disparity in moisture contents increase into September. This did not occur in this scenario.

There was a .68 MJm^{-2} difference in QE between the two simulations. Of this, .38 MJm^{-2}, resulted after two rainfall events near May 1, from increased precipitation and higher temperatures.

5.6.2 1991 CCC GCMII Scenario

1991 was categorized a normal/dry fire season. It was chosen for study to detect changes that may arise during fire seasons with below average amounts of precipitation. Danger indices were considerably higher than those in 1993. Two extended dry periods developed during the season that led to low moisture contents. Many periods of high danger were identified using the FWI program, and are visible in evaporation model output.

The lowest recorded moisture contents occurred during this fire season. Response due to climate change should be distinct. Table 5.7 compares 1991 original data to CCC GCMII output using the Halliwell model.

1991 had a SSR of 2.02 which is below the 40 year average of 2.26, but moisture contents would indicate a more severe fire season. Low moisture contents originated from well below average precipitation, and the timing of the rainfall. Most fell in June, but was preceded by a two month dry period. Following the month of June, another month and a half of dry weather developed. Temperatures were only average through the season, thus, fire danger was inhibited from reaching extreme levels. Model reaction is to dry the surface and soil through the fire season.

Table 5.7 1991 CCC GCMII Scenario.

Scenario	1991 Original Data	CCC GCMII
Sfc. MC	.617	.578
Soil MC.	.623	.585
Avg. Sfc. T	17.40C	21.15
Thaw Date	May 21	May 12
QH (Wm^{-2})	64.2	56.7
QE	68.9	75.3
Qg	11.9	13.2

The lower the moisture contents, the greater amount of rain is needed to increase moisture contents. 1991 had low moisture contents because it had extended periods of little, or no rainfall.

The amount of evaporation (QE) was relatively low. An average of only 68.9 Wm^{-2} of energy was partitioned to QE. QH was above average during the fire season (compared to other original data simulations). Less energy was needed to evaporate the low rainfall, thus, more energy was available to QH. This relationship may also be illustrated using the Bowen Ratio (β). β is defined as the ratio QH/QE. The partitioning of this energy has direct relevance to the boundary layer. A high QH and low QE produces a high ratio (>1), and acts as a channel for dissipating heat. Cool, dry days (low fire danger), may have similar quantities of QH and QE - where there may be little evaporation, but cool temperatures; increasing local humidity. Typical values are 0.4 to 0.8 for temperate forests and grasslands. (Oke 1987) A high β-ratio may indicate a warm, dry day (higher fire danger). These periods of high danger can be seen ahead in Figure 5.39, and compared to the figure depicting QE and moisture content (Figure 5.34).

The CCC GCMII scenario lowered moisture contents to low levels. A four percentage point decrease in moisture conditions was experienced. Largest change took place during the summer months. With an increase in precipitation during April and May, the reduction in moisture content was modified. During summer, large changes in moisture contents occurred. This is evident in Figure 5.34. The first stretch of dry weather (April 2 to May 10), led to a 2.5 percentage point difference between surface moisture contents. A second dry period (July 1 to August 16), led to a 6 percentage point difference between the two scenarios. With greater amounts of seasonal evaporation, the difference in moisture contents grew continually larger through the season.

A 1 mm decrease in precipitation resulted from the CCC GCMII scenario. Increased temperatures led to higher values of QE for the entire season (Figure 5.34). An increase in rainfall during the spring, combined with the warmer temperatures produced higher values of QE. During the summer, the amount of evaporation in the changed scenario was also greater, but not as much as in the spring.

With less energy used in evaporation, more energy was available to Qg. Thaw dates occurred nine days sooner with the climate change scenario.

Original moisture contents and daily QE values were compared high fire danger periods in the FWI model. During 1991, seven periods were identified representing high to extreme danger:

May 18 - 20
May 30 - June 2
July 21 - 25
August 4 - 5*
August 8 - 11*
August 14 - 18*
September 28 - 30

* 24,000 hectares burned in Lac La Biche Forest during August 4-18.

These periods are easily recognizable in Figure 5.36 showing original 1991 data, and the Bowen Ratio (Figure 5.39).

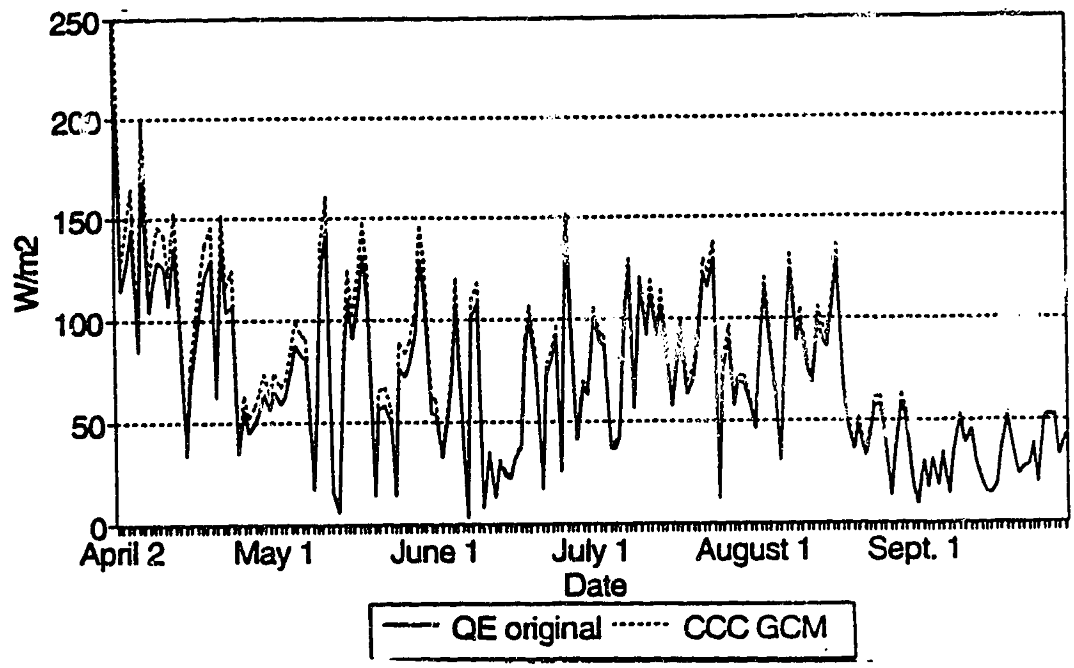


Figure 5.34 Daily QE values for original and CCC GCM simulations.

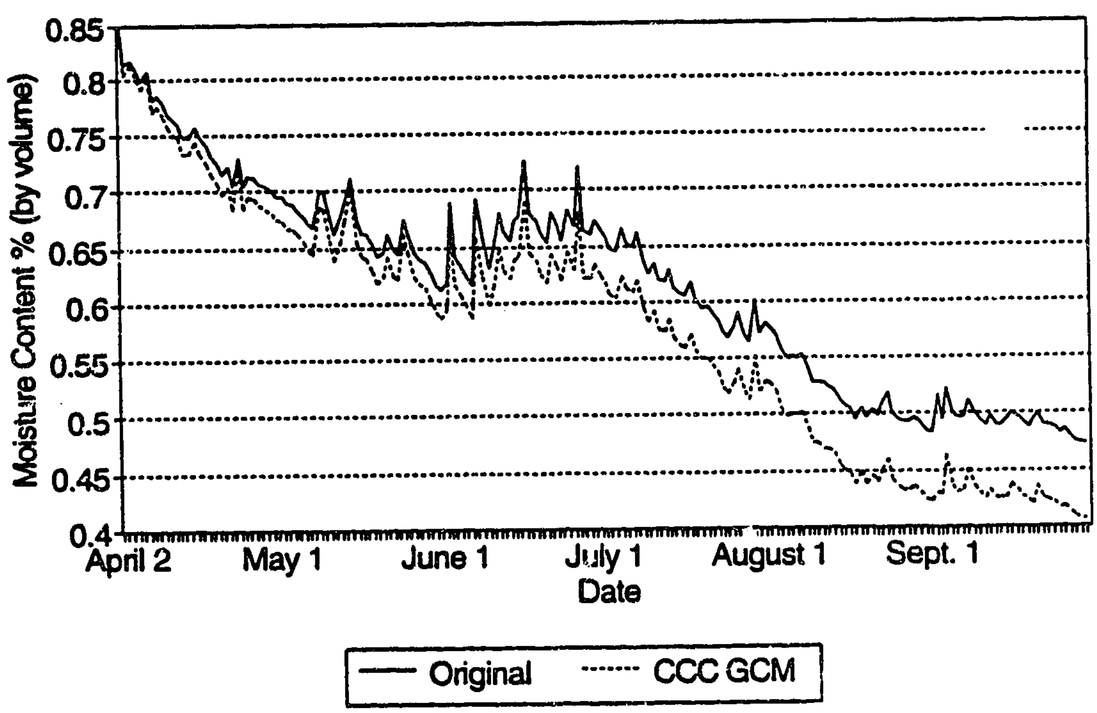


Figure 5.35 Seasonal surface moisture contents of original and CCC GCM simulations.

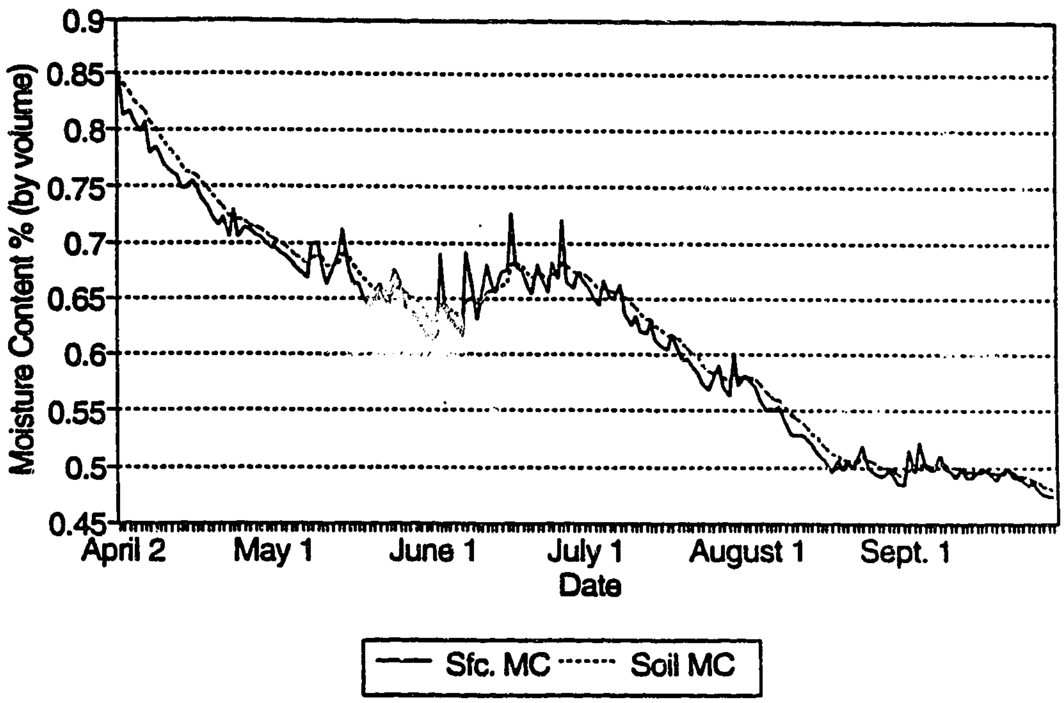


Figure 5.36 Surface and soil moisture contents from original data.

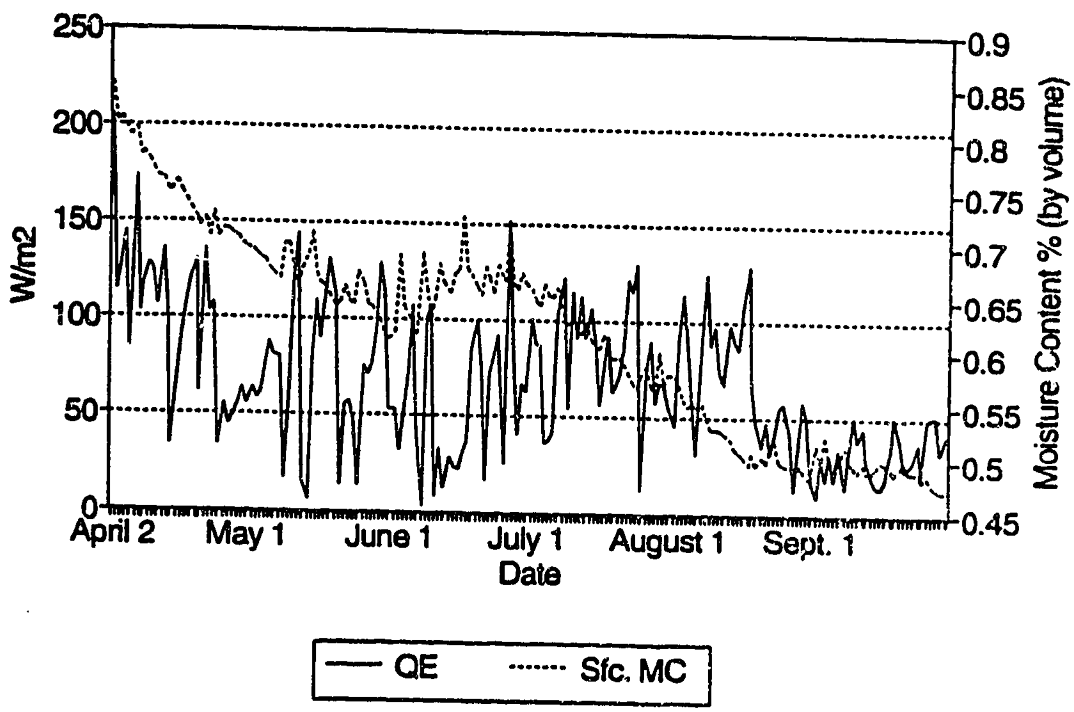


Figure 5.37 Seasonal QE and surface moisture content with original data.

During these short periods, large decreases in moisture contents are noticeable. The most obvious occurrence is in early August, where an 8 percentage point decrease in surface moisture contents occurs. Other periods are visible, but are not as dramatic.

The lowest values of QE produced in the Halliwell model may not occur during the period of declining moisture contents, but these periods do result in low evaporation rates. Surface moisture contents are more responsive in the original simulation during the summer months, with more precipitation and lower temperatures. The greater amounts of evaporation during the summer keep moisture contents from climbing quickly in response to rain. Periods of high danger are identified by large decreases in moisture contents coinciding with extended periods (widths) of low QE values (Figures 5.37 and 5.38). The seven periods of high danger listed above are visible.

Moisture content of the surface layer for both simulations are shown for the entire fire season in Figure 5.35. Moisture contents show increasing differences during the summer months with a maximum at the end of the fire season. The CCC GCMII simulation produces drier soils initially, and this difference increases over the course of the season. Once soils begin to dry, the rate of drying increases over time, and more precipitation is required to recharge the soil.

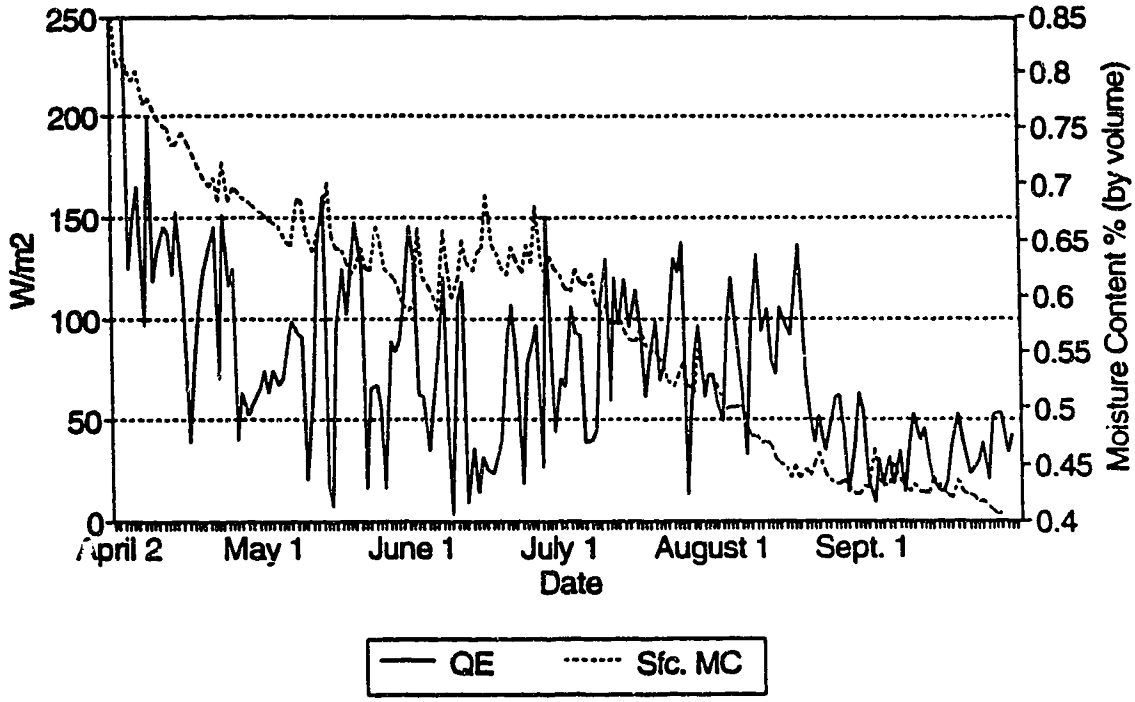


Figure 5.38 QE and moisture content from CCC GCM scenario.

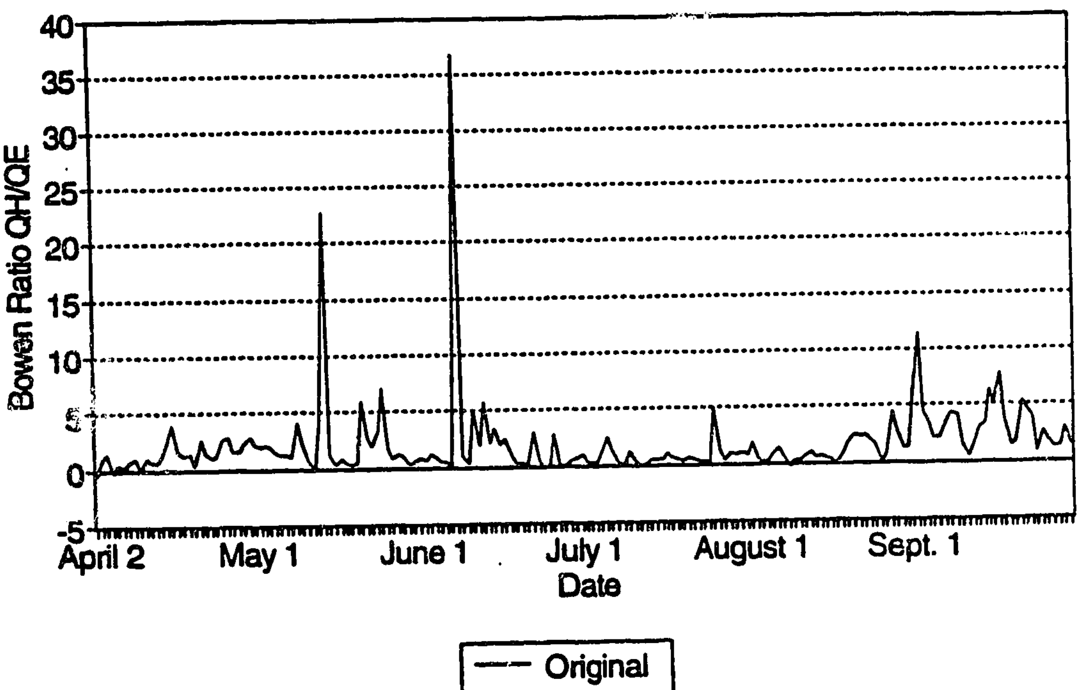


Figure 5.39 Bowen Ratio for original data.

5.6.3 **1990 CCC GCMII Scenario**

1990 was categorized a cool/dry year. It had a SSR of 2.63, which was higher than 1991, but had wetter soils over the length of the fire season because 58 mm more rain compared to 1991. The SSR had a greater value because higher windspeeds and warmer temperatures were experienced during the dry periods. There were five periods when moisture contents declined quickly. The CCC GCMII scenario decreased moisture contents by substantial amounts. Table 5.8 shows the results of the Halliwell model using original and climate change data sets.

Table 5.8 1990 CCC GCMII Scenario.

Scenario	1990 Original Data	CCC GCMII
Sfc. MC	.649	.609
Soil MC	.654	.615
Avg. Sfc. T	16.40	20.32
Thaw Date	July 13	May 28
QH (Wm^{-2})	47.8	52.8
QE	72.2	78.7
Qg	24.8	13.2

The CCC GCMII scenario produced a higher amount of QE. Warmer temperatures and 1 mm less precipitation increased QE by a daily change of 6.5 Wm^{-2}). Moisture contents were lowered by 4.0 percentage points, a result consistent with that experienced in above scenarios. The difference in QE was spread over the entire season. Unlike 1993, QE was consistently higher under the CCC GCMII scenario than the original. Larger variations took place early in the season than during the summer, but values were higher during the entire fire season. (Figure 5.40).

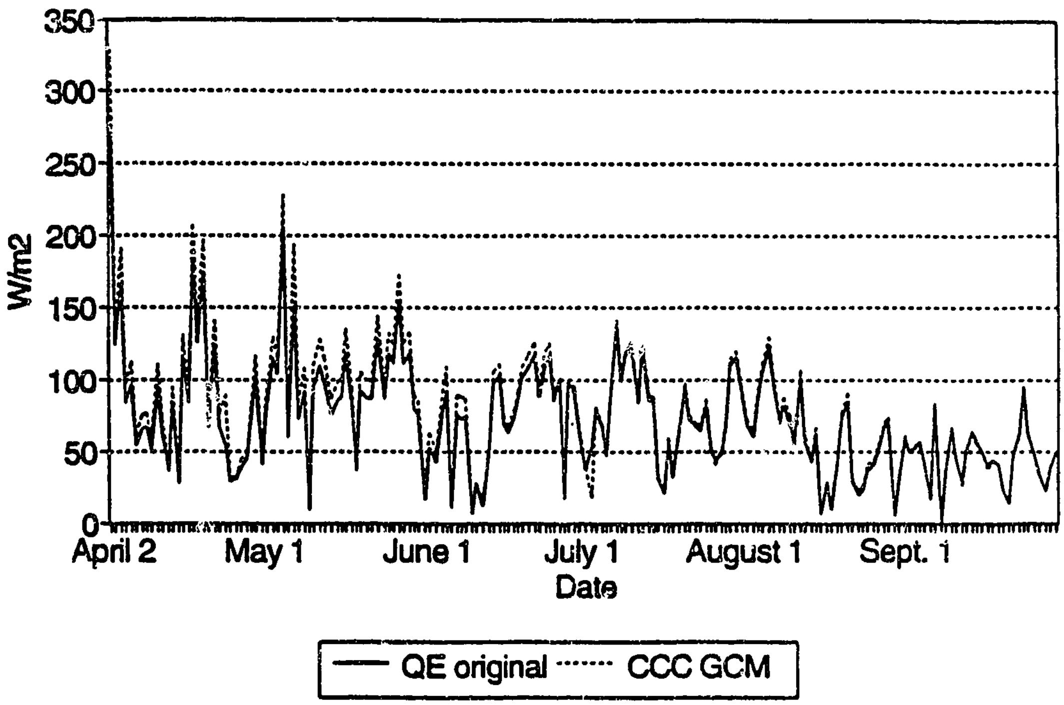


Figure 5.40 Seasonal QE values from original and CCC GCM simulations.

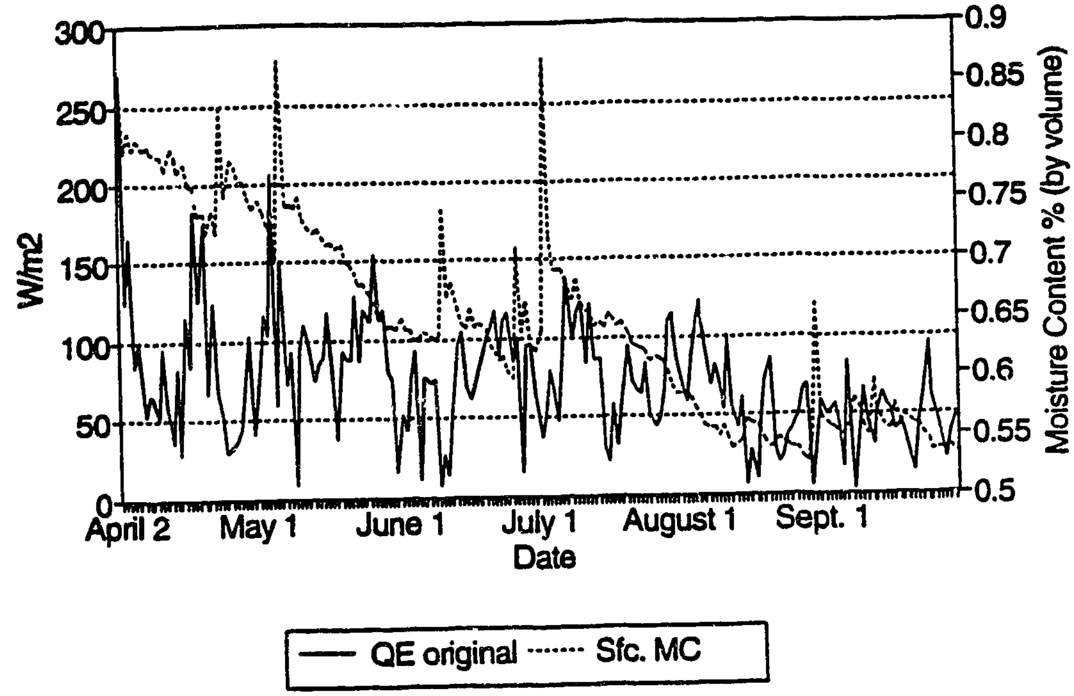


Figure 5.41 QE and surface moisture contents for original data.

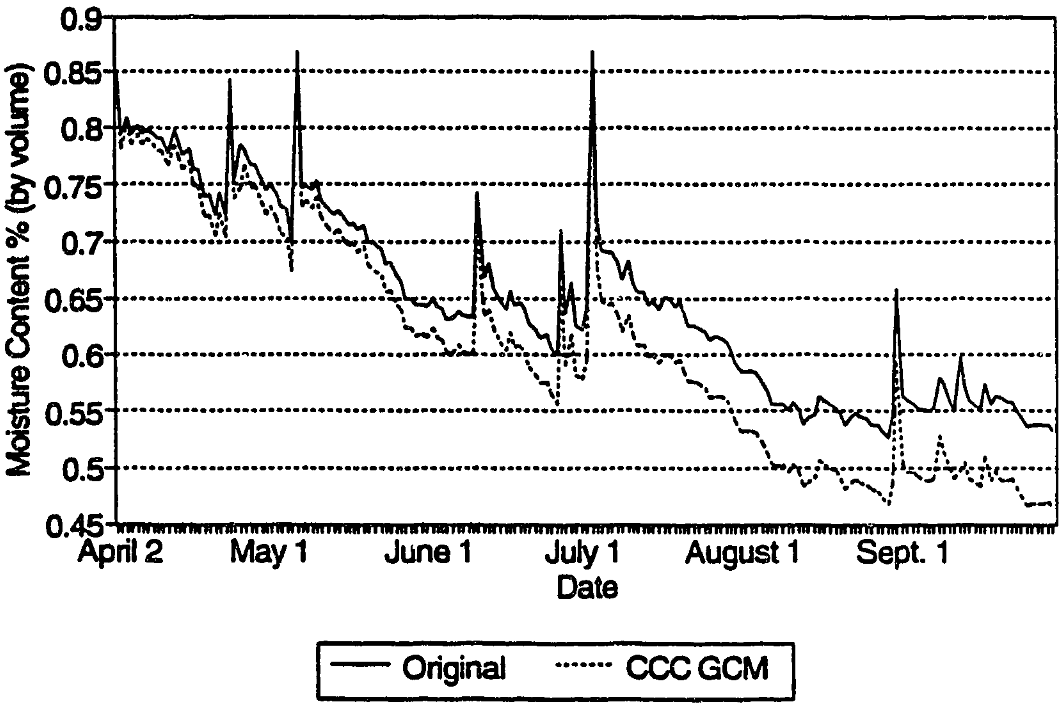


Figure 5.42 Seasonal surface moisture contents for original and CCC GCM scenarios.

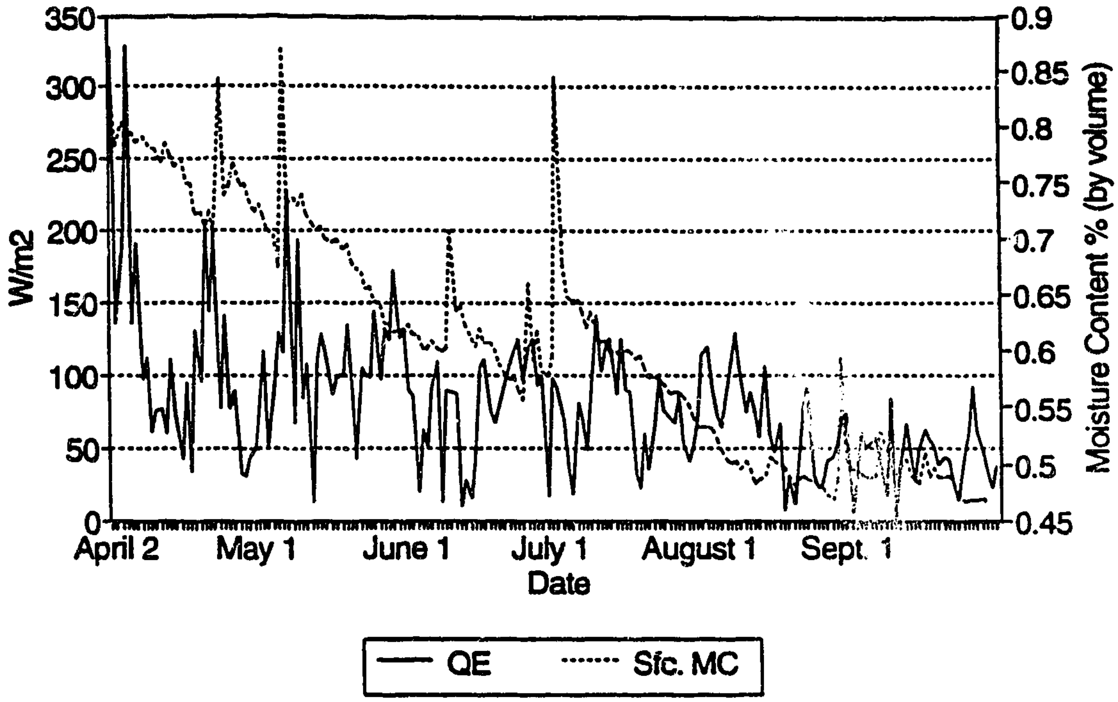


Figure 5.43 QE and surface moisture contents for CCC GCM scenario.

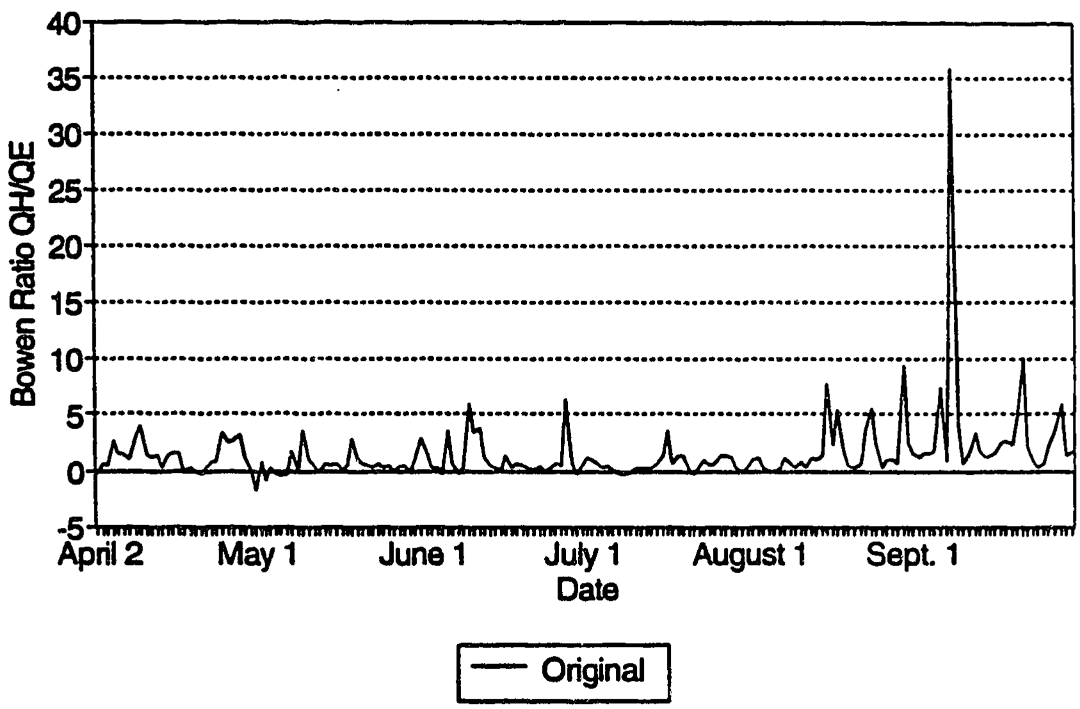


Figure 5.44 Bowen Ratio using original data.

Unlike other seasonal data sets, 1990 data had a large value of Qg; 24.8 Wm^{-2} which produced a thaw date of July 13, a figure that appears unrealistic. The original fire weather data showed many below freezing or 0°C days occurred during the spring, especially before May 15. This led to many days where frost developed, in the model, immediately below the surface layer. More energy was then allotted to Qg to thaw the soil, and thus increased the seasonal value of Qg. When the original data was run with the CCC GCMII scenario, temperatures increased enough to inhibit frost development. Because of this, less energy was partitioned to Qg and its seasonal value was consistent to other scenarios.

Two major drying trends developed in 1990. They produced seven periods of high danger. Moisture contents during these periods declined by substantial amounts. Change ranged from 13 to 18 percentage points over the two long dry periods. Nearly the entire month of August had low values of QE (~55 Wm^{-2}). These low evaporation rates were the result of low moisture contents in the surface and soils, and can be seen in Figure 5.41, and by the Bowen Ratio (Figure 5.44).

Moisture contents were consistently lower with the CCC GCMII scenario. During spring, moisture contents were marginally lower than those of the original simulation. Moisture contents were even higher after one precipitation event (Figure 5.42 (late April)). The impact of less rain and warmer temperatures again led to increasing discrepancies between the two simulations. A 2 percentage point difference on May 1 increased to 6 percentage points at the end of September. If this trend was to continue more precipitation will be needed to recharge soil moisture to alleviate the possibility of dr(ight. If moisture is not recharged, initial moisture cont nts in the spring would be lowered and this would be carri into the next fire season.

With lower moisture contents, the number of days of high danger in the fire season should increase, as they do in the FWI model. The FWI model had an increase of 18 days with the CCC GCMII scenario. The FWI model produces daily indices that enables the user to categorize the danger level for each day. The Halliwell model does not provide one value that allows the user this privilege. Instead, evaporation rates need to be investigated. The number of days rated high danger were counted in the FWI model for all fire seasons and were then compared to evaporation rates. A relationship was discovered between the two. Days with QE < 45 Wm^{-2}, appear to be the threshold, and correspond to high danger days. The number of high danger days in the FWI model were approximately equal to the number of days that had QE values equal to, or below 45 Wm^{-2}, a value equivalent to 3.8 mm of evaporation per day. This value, or below, indicates that very little moisture is available for evaporation and that the fuels are in a very dry state.

Seven periods of high danger developed during 1990. These periods are easily identified when daily QE values are compared to moisture contents (Figure 5.43). Rapid declines in moisture contents are mirrored by extended periods of low daily QE values (below 50 Wm^{-2}). An obvious example occurs near May 1. There is a decline in moisture contents that coincides with lower evaporation rates. A five day stretch exists where QE remains below 50 Wm^{-2}. Moisture contents during this time would be conducive to fire if a fire starting agent is presented. Other periods where moisture contents decrease exhibit the same characteristics.

5.6.4 **1977 CCC GCM Scenario**

1977 was a cool/wet year. The characteristics shown by the data should be very similar to that of 1993. That is, the climate change scenario should not affect fire danger significantly. Moisture contents should be slightly lower than 1993 values because 1977 was 1.15°C warmer and received 40 mm less precipitation. Seasonal statistics for 1977 are as seen in Table 5.9.

Moisture contents remained relatively high for most of the season. Following an initial dry stretch in April, where moisture contents declined 20 percentage points, regular rain maintained moisture contents around 0.65. With original data, daily average QE was 74.0 Wm^{-2}.

Table 5.9 1977 CCC GCMII scenario.

Scenario	Original Data	CCC GCMII
Sfc. MC	.677	.649
Soil MC	.680	.653
Avg. Sfc. T	16.36	20.15
Thaw Date	June 1	May 15
QH (Wm^{-2})	37.3	30.9
QE	74.0	82.6
Qg	15.5	13.1

74.0 Wm^{-2} was the second highest daily average recorded. Only 1993 original data had a higher value. This value increased to 82.6 Wm^{-2} under the climate change scenario, and lowered moisture contents by 0.27 percentage points. This is a small decrease with the climate change scenario using the Halliwell model.

The changed scenario produced higher values of QE over the entire season. The difference was larger during the spring months, but was maintained during the summer months at lower levels.

Surface moisture contents in both scenarios, were similar for most of the fire season. Only from mid-August on did moisture contents increase using the CCC GCMII scenario. Slightly less rainfall during this time allowed this to occur. By the end of September this difference narrowed again, following heavier precipitation events.

Only two periods of high danger were identified by the

FWI model. These occurred early in the fire season during the only dry stretch. April 12 - 25, and May 1 - 2 are the only times where fire danger was high. During April 12 - 25, surface moisture contents decreased 10 percentage points. At this time QE had a stretch of low daily values, although not its lowest seasonal values. The amount of net energy reaching the forest floor during the spring is relatively high, as leaves have not yet developed to block this radiation. The values of QE were low relative to the time of year.

The second, short, period of high danger (May 1 - 2), saw moisture contents decrease 4 percentage points. During this time, QE values were significantly below 50 Wm^{-2}. This was the second longest stretch of low values experienced during the fire season, and can be seen in Figure 5.45.

1977 data are very similar to that of 1993 and may confirm the theory that years with a high amount of rainfall will not be as affected by climate change as drier years. The decrease in moisture contents do not produce a high fire danger. The FWI model show only four additional days of high danger with a climate change scenario.

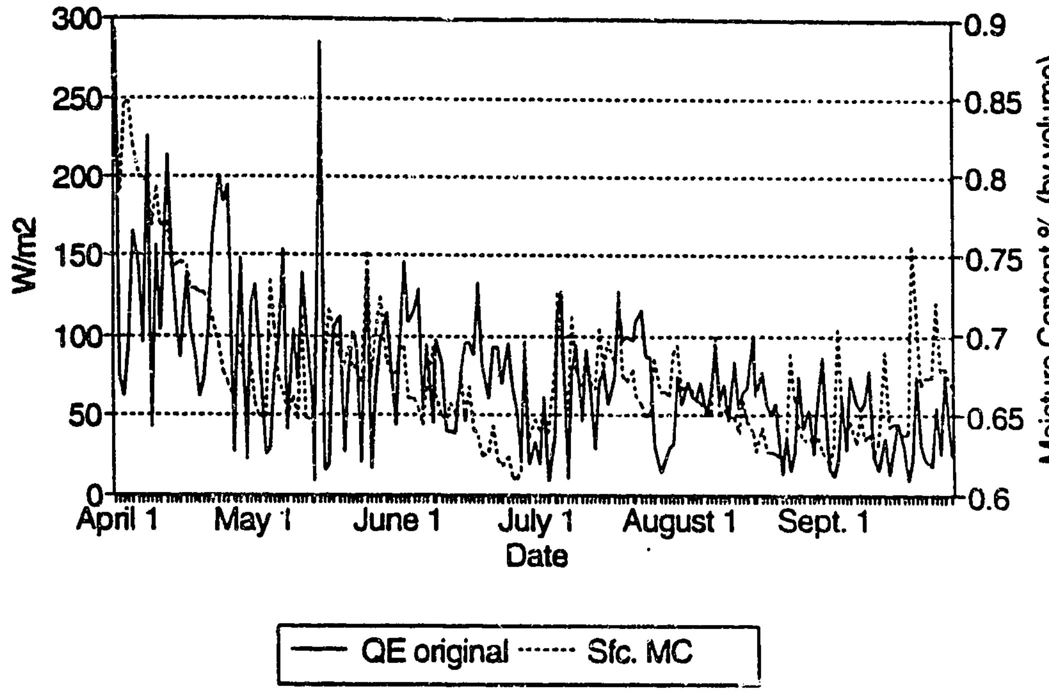


Figure 5.45 QE and surface moisture content using original data.

5.6.5 **1988 Altered Precipitation Scenario**

1988 fire weather data was chosen for analysis to discover the effect altering the timing of precipitation has on the resulting fire danger. The FWI model produced a large increase in the SSR for 1988, with a change in the timing of rainfall combined with the CCC GCMII climate change scenario. An eight day period at the end of May was moved forward into the fire season. This same scenario was run through the Halliwell model. Results of the CCC GCMII scenario, along with original data, is listed in Table 5.10. 1988 was originally categorized a cool/normal fire season, with a low seasonal fire danger.

The new scenario increased fire danger to a moderate rating. Twenty-eight more days occur in the high danger rating category - a large increase. The Halliwell model produced a decrease in average moisture contents of 4.6 percentage points for both moisture contents. The largest change coincided with the change in timing of precipitation. During late May, the original data (Figure 5.46) experiences a rapid decline in moisture contents. By moving the June rainfall ahead 8 days into the summer, moisture contents decreased to low values. Original data produced a moisture content (at the beginning of the dry period) of 0.67. The CCC GCMII scenario had a moisture content of 0.64 at this time. Thus a difference of 3 percentage points existed.

Table 5.10 1988 altered precipitation scenario.

Scenario	Original Data	Altered P and CCC
Sfc. MC	.670	.624
Soil MC	.675	.629
Avg. Sfc. T	16.70	20.94
Thaw Date	May 22	May 11
QH (Wm^{-2})	59.7	54.0
QE	79.1	84.0
Qg	12.2	13.1

Moving the start of precipitation ahead 8 days allowed moisture contents to decrease to 0.53. The original simulation had contents equalling 0.61, giving a difference of 8 percentage points between the two sensitivity tests.

Moisture contents in the altered scenario were then in the high danger range. Figure 5.47 illustrates the change in moisture contents of the two scenarios.

The change resulting from the altered timing is obvious. Moisture contents decline to low values in the altered simulation. From this period on, moisture contents remain 6 percentage points below those of the original test. The Halliwell model was oversensitive to heavy precipitation on one occasion. Near the beginning of July, a heavy rainfall led to maximum surface moisture contents. Immediately after, the model responded by drying the surface to unrealistic values for one day. This response occurred in both sensitivity tests. The common pattern of increasing disparity between moisture contents as the summer progresses is also evident in this simulation. Increased temperatures and less precipitation during the summer act to increase the difference in soil moisture.

The value of QE increased 76.8 MJm^{-2}, seasonally, in the changed scenario. Most of this increase occurred during the months of April and May. During the summer months QE was larger in the original simulation, especially around June 1. Moving precipitation ahead 8 days did not lower QE as much as expected in the climate change scenario. The model did react with an extended period around 100 Wm^{-2} (daily means) which are low values for May, but was influenced by the 32% greater precipitation during this period.

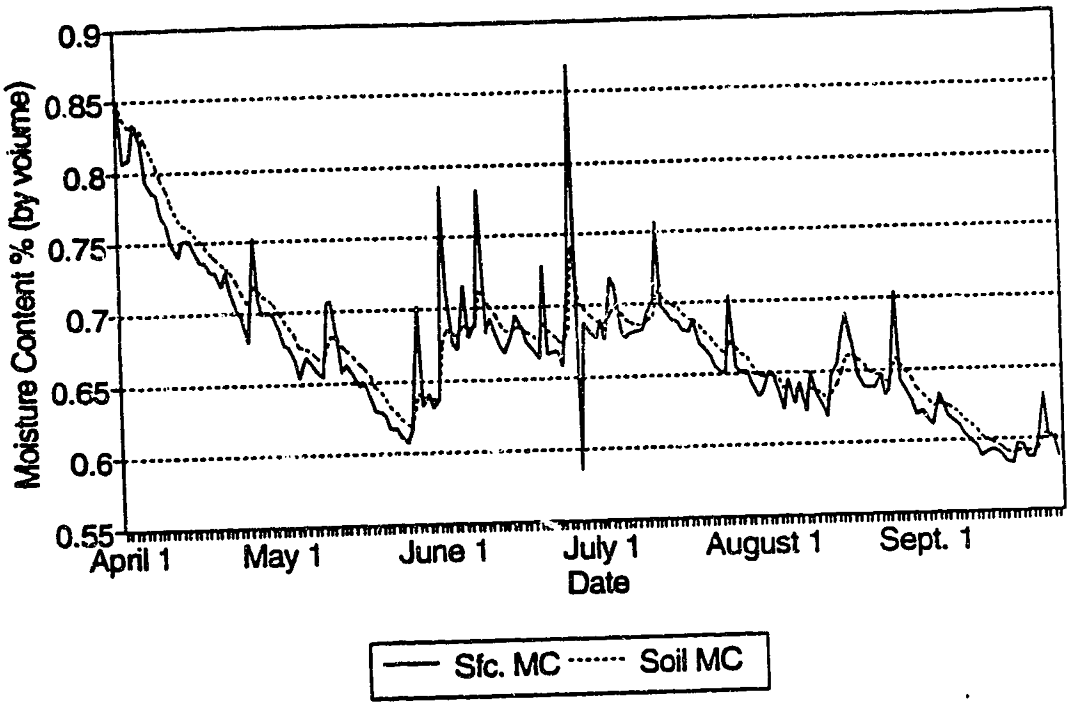


Figure 5.46 Surface and soil moisture contents using original data.

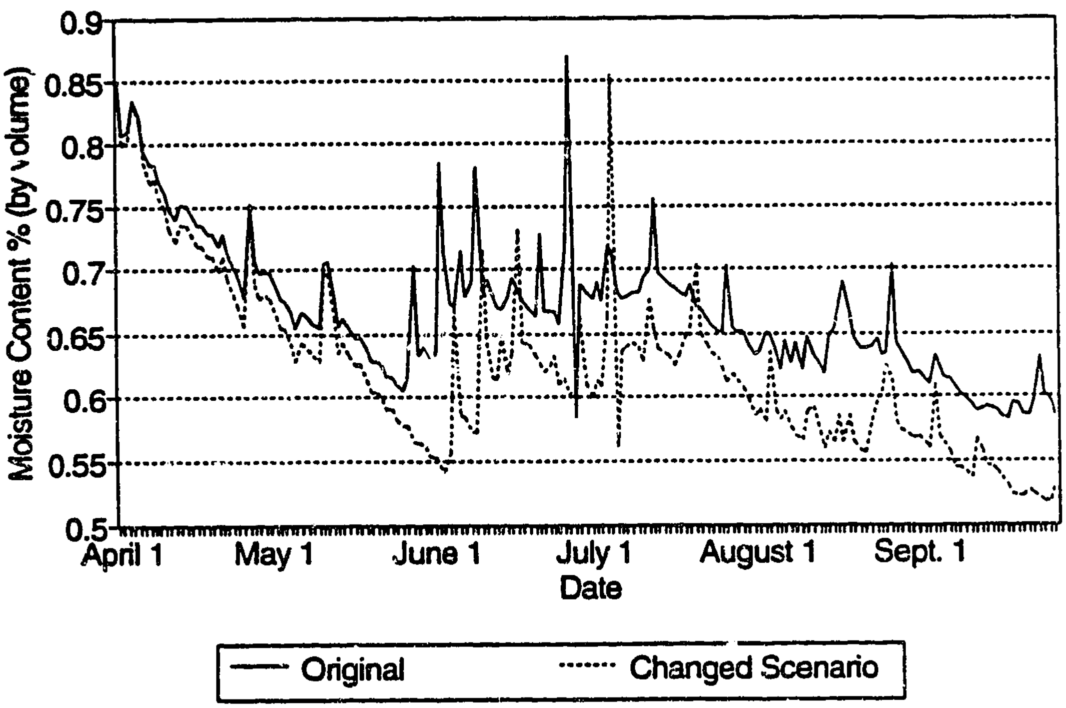


Figure 5.47 Surface moisture contents for original and altered precipitation simulations.

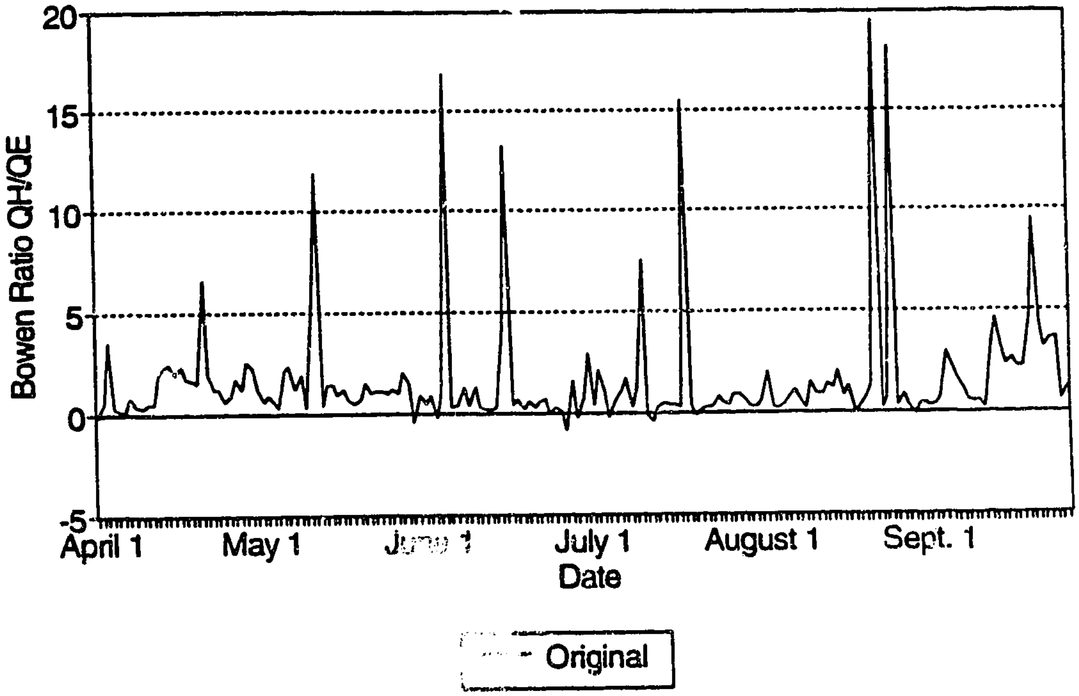


Figure 5.48 The Bowen Ratio using original data.

Original data show this dry period having low values of QE. There is an extended period of below 100 Wm^{-2} values at this time a trend that is also visible using the β-ratio (Figure 5.48). The β-ratio was well above one for an extended period of time.

A larger seasonal averaged value of Qg resulted in an 11 day change in the thaw date, a moderate change compared to other simulations. The influence of the precipitation timing change did not have a large influence on this date.

A change in the timing of precipitation combined with the CCC GCMII scenario had a large impact on the fire danger using this data. The extended period of dry weather decreased moisture contents to low levels and was followed by moisture contents that did not recover to previous higher values. The dry period would produce an increased fire danger for the entire season following the initial change in rainfall patterns. 1968 was not one of the highest rated danger seasons, but the change in danger was substantial. If cloud data were available for 1970, or another year that was categorized as high danger, the change may be profound. The FWI model estimated a higher than normal change in SSR with this scenario. A year that was categorized as high danger may undergo greater change.

Chapter 6

Conclusion

The first objective was to validate the FWI model using moisture contents gathered in the field. Actual moisture contents mirrored the response to climatic influences as those estimated by the FWI model. There were differences between the two data sets, but the similarity in the patterns encouraged the use of the FWI model for illustrating periods of fire danger using historic data.

The second objective was to initialize and test the Halliwell model for use in a boreal forest environment. The model was initialized using general site measurements, an estimated soil profile, a logarithmic wind profile above the canopy, and an approximation of net radiation under the canopy. Tests were run, and model coefficients were adjusted, primarily based on the model's response to precipitation.

The third objective was to determine a most-likely scenario of future climate at a regional scale. Output was used from the CCC GCMII model, and techniques were employed to utilize this data at a regional scale. The timing of precipitation events - extremely important to fire danger

- was included. Even though this may be a form of weather forecasting, and is currently unpredictable by GCMs, its importance to fire danger required its simulation.

The final objective was to identify changes in fire danger in response to altered climatological influences by performing sensitivity analysis with both the FWI and Halliwell models.

Historic data were used in the FWI model to categorize fire seasons, based on climatic normals, and compared to hectares burned for their respective fire season. Temperature and precipitation were used to categorize season types. The number of days each season type experiences in the high danger range were investigated, as short periods of extreme fire weather are usually responsible for many hectares burning. Warm temperature seasons produced greater high danger days than seasons with below normal precipitation. They also produced higher SSR's. Because of this temperature is believed to have a greater influence on fire danger. Cool seasons had lower SSR's than wet years. When the chosen climate change scenario was imposed on the time series, SSR's increased 37.5%, and the largest influence occurred in years with normal temperatures. 10% more days would occur under the changed scenario (18 for the season), and these would occur during the summer months, coinciding with the lightning season. The timing of the high danger days would thus shift from late spring to mid-summer.

Sensitivity tests were performed using the FWI model to determine the influence proportional drying power of each variable in the model. Temperature was the most important variable, alone or in combination with others.

Fire danger is heavily influenced by short periods of extreme weather. Present GCMs can not estimate these periods of weather. They produce monthly anomalies that are unable to give insight into these potential changes that can influence fire danger. Therefore, scenarios based on climate patterns describing the Lac La Biche region were included that altered the timing of rainfall events. Results of these simulations revealed that timing is crucial when related to fire danger. Moisture contents declined to levels producing high danger, with the largest change in the DMC index. SSR's were found to increase 8%, with just a change in timing - this did not include the CCC GCM scenario. A change in timing and the changed scenario increased SSR's 30%, from the original data.

The CCC GCM scenario used in this research led to moisture contents of forest fuels declining as much as 10%, even with a large increase in precipitation in the spring and fall months. The CCC GCM estimates a 6.6% decrease in soil moisture.

The Halliwell model was set up and performed the same sensitivity test as the FWI model. The Halliwell model tested the sensitivity of the model to five elements. These were: temperature, vapour pressure and precipitation, Q* and wind speed, and were organized from greatest to least sensitivity. These results were encouraging considering the imprecision of the methods used to estimate Q* and the use of the wind speed profile. Because the influence of Q* and the wind speed profile were very small in the sensitivity tests, the potential errors associated with them would also remain small. The model produced results that showed the same patterns as the FWI model and soil moisture contents were similar to estimates of the CCC GCM. Average decreases in moisture content were 3% for wet seasons, and 4% in normal and dry seasons. Change was smaller during the wetter seasons, and substantial during normal and high danger seasons.

Changing the timing of precipitation was also found to be very important in sensitivity tests in this model. The timing scenario was included to illustrate its importance to fire danger. During the periods when precipitation was moved ahead into the season, the extra week of dry weather lowered moisture contents to very low levels. The CCC GCM scenario also showed how moisture contents decrease at a larger rate than under regular scenarios on a seasonal basis. With an increase in temperatures, more moisture will be needed to replenish the soils. Drought conditions may occur if over-winter precipitation does not recharge the soils. Even with increased precipitation, moisture contents declined in the

CCC GCM scenario. Higher temperatures and the increase in precipitation led to very high production of QE which acted to dry the soils. Dry periods were strongly influenced by the CCC GCM scenario. Greater amounts of evaporation took place, lowering ground fuel moisture contents to more dangerous levels. As in the FWI model, wet years were not influenced by the changed scenario. Already-high levels of QE were maintained.

Individually, wind speed and Q* had minor effects in model sensitivity tests. Cooler temperatures caused moisture contents to respond more dramatically than increased temperatures. Vapour pressure was an important variable in the testing of the model partly due to its relationship to both temperature and precipitation.

A relationship was found to exist between fire danger and QE. Extended low periods of QE quantities, where Bowen Ratios are greater than one, indicate periods of high danger. The partitioning of fluxes (QH and QE) show a moisture deficit on the surface.

Due to the similarity of results in the pattern of moisture contents between the two models, and the low sensitivity of the Halliwell model to the estimates of Q* and the chosen wind profile, encouraging results were produced. Both models revealed moisture contents may decline in the future under a climate change scenario and have an impact on future fire danger.

Future research would allow certain aspects in the model to be investigated. The first would be to gather actual Q* data under the forest canopy and allow a comparison with the estimated quantities of Q*. Model sensitivity to Q* was found to be very low, but actual data would be useful.

The second modification would be to try an develop a more accurate wind profile to describe conditions within a forest. Model sensitivity to this variable was also minor, but it could increase the model's acceptability.

The third change would be to attempt an hourly time step to allow a more precise description of evaporation in the model. Hourly data would be needed, but the model would not describe a heavy shower as a full day of precipitation. The model was very sensitive to large amounts of daily rainfalls. By including an hourly time step the model's present response may be modified especially if increases in precipitation amounts occur with climate change.

Even though this was not a research project that tried to replicate results from other research, findings were similar. The Halliwell model produced changes in moisture contents that were similar to those estimated by the CCC GCMII, and those estimated by the FWI model. Because of this, an acceptable degree of confidence exists for the use of this model in a boreal forest environment to study moisture contents and fire danger.

A model was tested that can be used with simple inputs, and is applicable in any forested area. It has shown how moisture contents are influenced by climatic variables and what some of these variables are. It also revealed the importance of timing, especially of precipitation, on fire danger.

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