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Front Cover: Structure of the Canadian Forest Fire Behavior Prediction (FBP) System.

INTRODUCTION

The inaugural meeting of the Western Region Fire Weather Committee (WRFWC) was held at the Atmospheric Environment Service's (AES) Western Region office in Edmonton on January 8, 1976. Since then, the committee has meet on an annual basis in the fall or early spring. WRFWC member agencies currently include:

Alberta Forest Service
Atmospheric Environment Service, Western Region
Forestry Canada, Northwest Region
Northwest Territories Department of Renewable Resources, Territorial fire Centre
Parks Canada, Prairie and Northern Region and Western Region

In 1983, half-day scientific and technical seminars began to be held every other year in conjunction with the committee meeting. The goal of these sessions was to reacquaint meteorologists required to make fire weather forecasts with the problems associated with forest fires. These have been excellent opportunities for foresters and meteorologists, both in the operational and research aspects, to gather and present their current work.

This is now the fourth proceedings to be prepared by Forestry Canada for the scientific and technical session. I hope that you find the collection of papers as interesting as I have.

Kerry Anderson
WRFWC committee chairman 1992-1993

A BRIEF OVERVIEW OF THE CANADIAN FOREST FIRE BEHAVIOR PREDICTION (FBP) SYSTEM[1]

Kelvin G. Hirsch[2]

INTRODUCTION

The Canadian Forest Fire Behavior Prediction (FBP) System is the one of four subsystems of the Canadian Forest Fire Danger Rating System (CFFDRS). It has been under development since 1968 when a modular approach to a national system for fire danger rating was envisioned (Figure 1). Other subsystems of the CFFDRS are the Canadian Forest Fire Weather Index (FWI) System, which was implemented by operational fire management agencies in Canada in the early 1970s; the Canadian Forest Fire Occurrence Prediction (FOP) System and the Accessory Fuel Moisture System both of which are still in development (Stocks et al. 1989).

The FBP System was developed by the Forestry Canada Fire Danger Group[3] in order to provide a national system for predicting fire behavior. An interim edition of the system was released in 1984 (Alexander et al. 1984) and documentation of the first complete version is now available (Forestry Canada Fire Danger Group 1992). Given that a formal technical report on the FBP System has been published, the purpose of this paper is to provide a brief overview of the system, its key inputs and outputs, and some of its primary operational applications.

NATURE OF THE FBP SYSTEM AND ITS DEVELOPMENT

The FBP System is primarily empirical in nature; many of the relationships within the system are based on observations of actual fire behavior. Information from a total of 495 fires (409 experimental fires and 86 well-documented wildfires) are included in the FBP System data base (Table 1). The FBP System data base also consists of observations from 345 fires from across Canada (Figure 2) as well as 18 fires from 6 areas in the northern United States and 132 Australian grass fires.

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[3] Current members of the Fire Danger Group are: R.S. McAlpine - Chairman (Petawawa National Forestry Institute), B.J. Stocks and T.J. Lynham (Great Lakes Forestry Centre), M.E. Alexander (Northern Forestry Centre), B.S. Lee (Northern Forestry Centre), and B.D. Lawson (Pacific Forestry Centre). Also a major contribution to the development of the FBP System was made by C.E. Van Wagner who recently retired from the Petawawa National Forestry Institute.

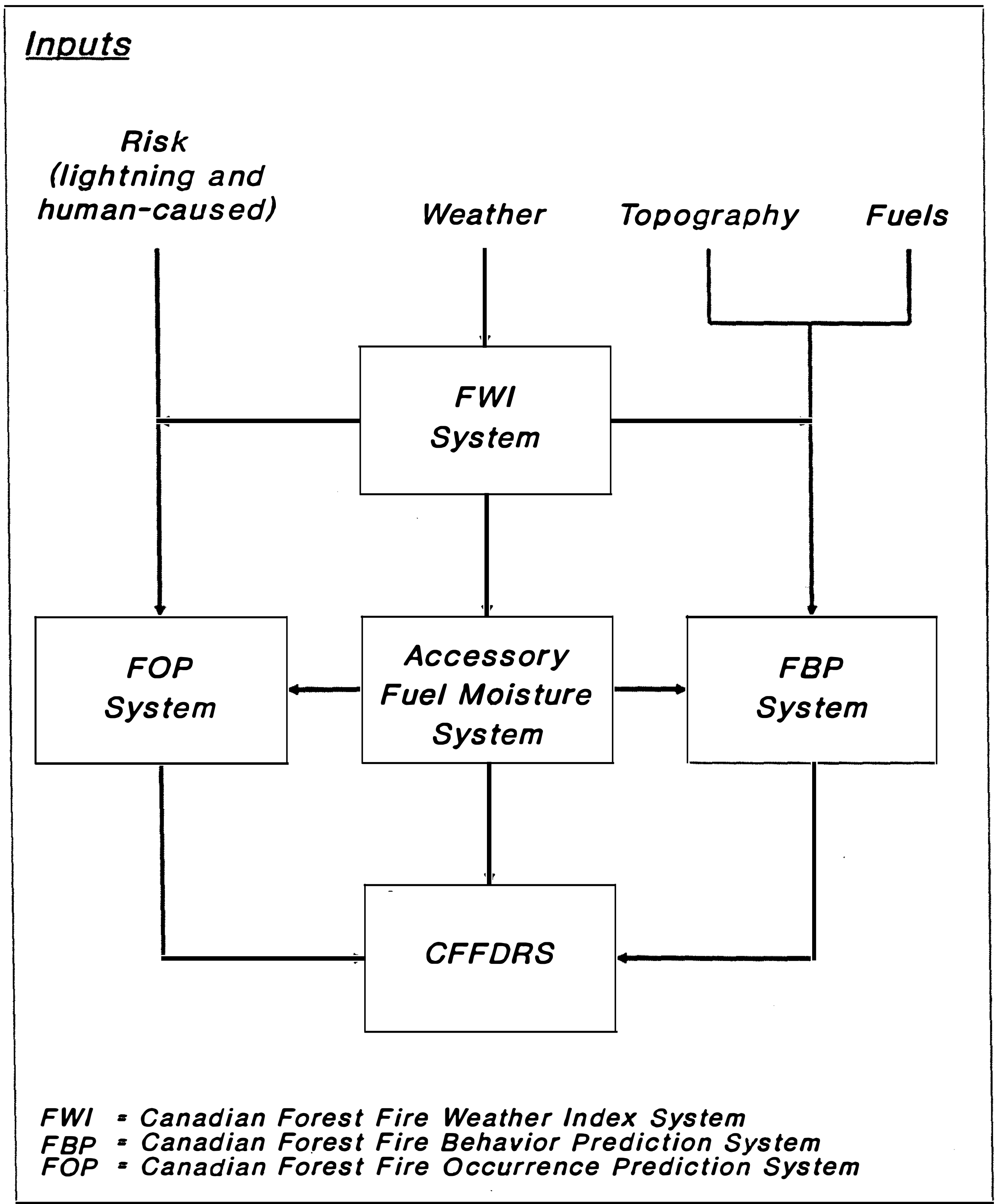

Figure 1. Simplified structure diagram for the Canadian Forest Fire Danger Rating System.

Table 1. Type and number of fires in the FBP System data base.

Fuel type	Experimental	Wildfires[a]	Total
Coniferous			
(C-1) Spruce-Lichen Woodland	7	1	8
(C-2) Boreal Spruce	18	30	48
(C-3) Mature Jack or Lodgepole Pine	41	22	63
(C-4) Immature Jack or Lodgepole Pine	15	20	35
(C-5) Red and White Pine	19	1	20
(C-6) Conifer Plantation	12	0	12
(C-7) Ponderosa Pine/Douglas-fir	8	5	13
Deciduous			
(D-1) Leafless Aspen	32	3	35
Mixedwood			
(M-1) Boreal Mixedwood-leafless[b]	---	---	---
(M-2) Boreal Mixedwood-green[b]	---	---	---
(M-3) Dead Balsam Fir/Mixedwood-leafless	5	0	5
(M-4) Dead Balsam Fir/Mixedwood-green	1	0	1
Slash			
(S-1) Jack or Lodgepole Pine Slash	48	11	59
(S-2) Spruce/Balsam Slash	49	21	70
(S-3) Coastal Cedar/Hemlock/Douglas-fir Slash	28	5	33
Open			
(O-1a) Matted Grass[c]	52	6	58
(O-1b) Standing Grass[c]	74	---	74
TOTAL	409	125	534[d]

[a] The wildfire category also includes a few well-documented operational prescribed burns conducted in the slash fuel types.
[b] The M-1 and M-2 fuel types are derived mathematically from the equations for C-2 and D-1.
[c] The O-1a and O-1b fuel types are based on Australian grass fire data that was analyzed by the Forestry Canada Fire Danger Group.
[d] A total of 39 wildfire observations were used in more than 1 fuel type (mostly C-2, C-3, and C-4) because a combination of these fuel types were consumed during the major wildfire runs.

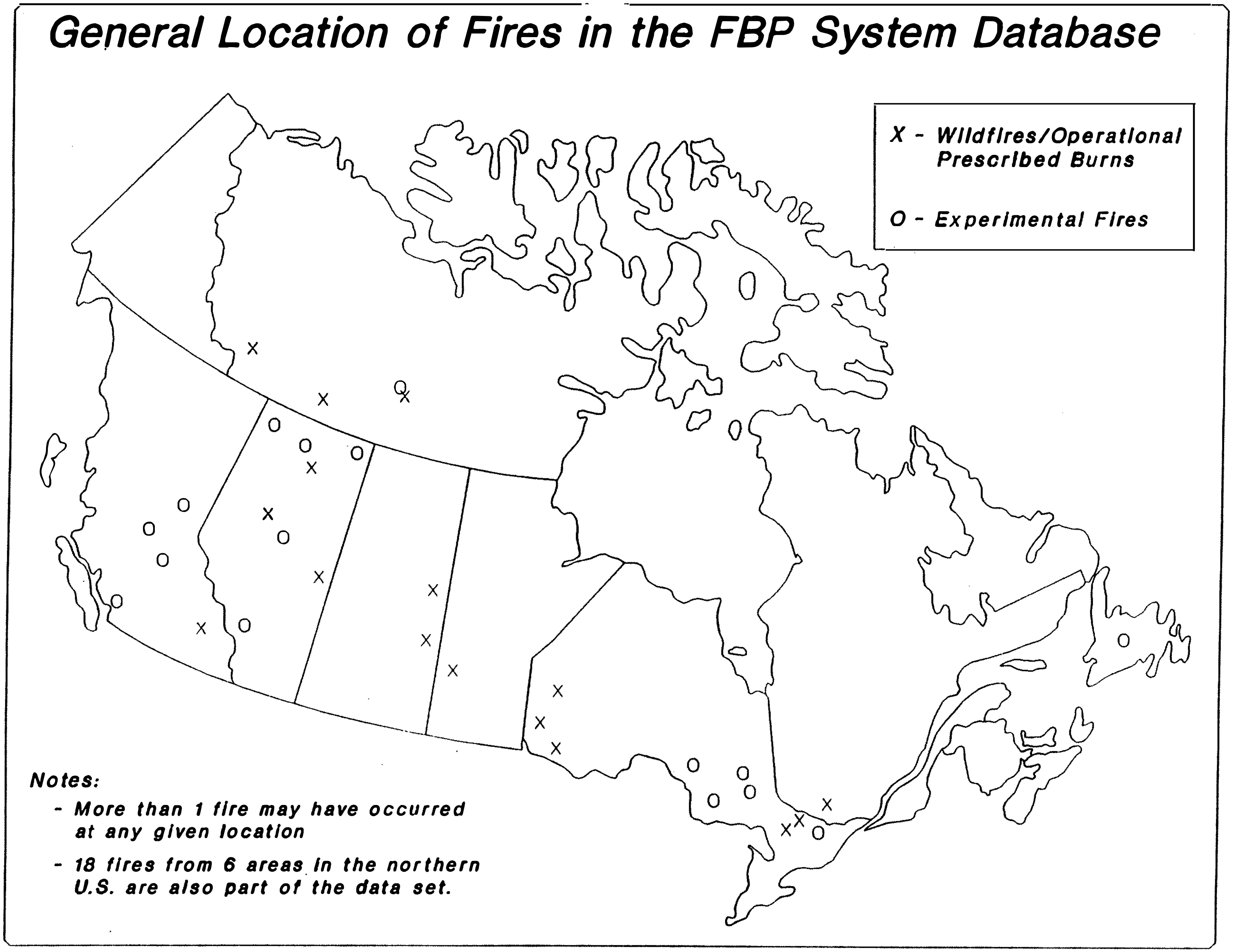

Figure 2. General location of fires in the FBP System data base.

To develop the FBP System the set of empirical fire data was analyzed using simple mathematical models and correlation techniques. Laboratory-based fire research in moisture physics and heat transfer theory was used as a framework for explaining the results of the data analysis. Physical theories of fire behavior were assessed in relation to the actual data to ensure that the most logical predictions were provided by the FBP System. These analysis and modelling activities were conducted jointly by the members of the Fire Danger Group allowing for the discussion of a wide variety of opinions and considerations.

STRUCTURE OF THE FBP SYSTEM

The FBP System has 14 primary inputs that can be divided into 5 general categories: fuels, weather, topography, foliar moisture content, and type and duration of prediction (Figure 3). In the FBP System these inputs are used to calculate 4 primary and 11 secondary outputs. Primary outputs are based generally on the fire intensity equation developed by Byram (1959), and secondary outputs are derived from a simple elliptical fire growth model (e.g., Van Wagner 1969).

Inputs

(a) Fuel Types

The FBP System has 16 general fuel types (including 7 coniferous, 1 deciduous, 4 mixed-wood, 3 slash, and 1 open or grass type) which represent most, but not all, of the major fuel types found in Canada (see Table 1). A poster with representative photographs of each fuel type is also available (De Groot 1992).

(b) Weather

The FBP System uses the Fine Fuel Moisture Code (FFMC), the Initial Spread Index (ISI) and the Buildup Index (BUI) from the FWI System (Van Wagner 1987). These indexes are considered weather inputs because they are calculated from observations of temperature, relative humidity (RH), wind speed and precipitation. The FBP System can also use detailed (e.g., hourly or time of day) observations or forecasts of wind speed (km/h) and wind direction (Figure 4).

(c) Topography

Percent slope and upslope direction are necessary inputs when the effects of topography on fire behavior are considered. Percent slope directly impacts on the rate of fire spread and the interactive effect of upslope direction and wind direction are used to predict fire spread direction. Note that upslope direction is the opposite of aspect (i.e., add or subtract 180°).

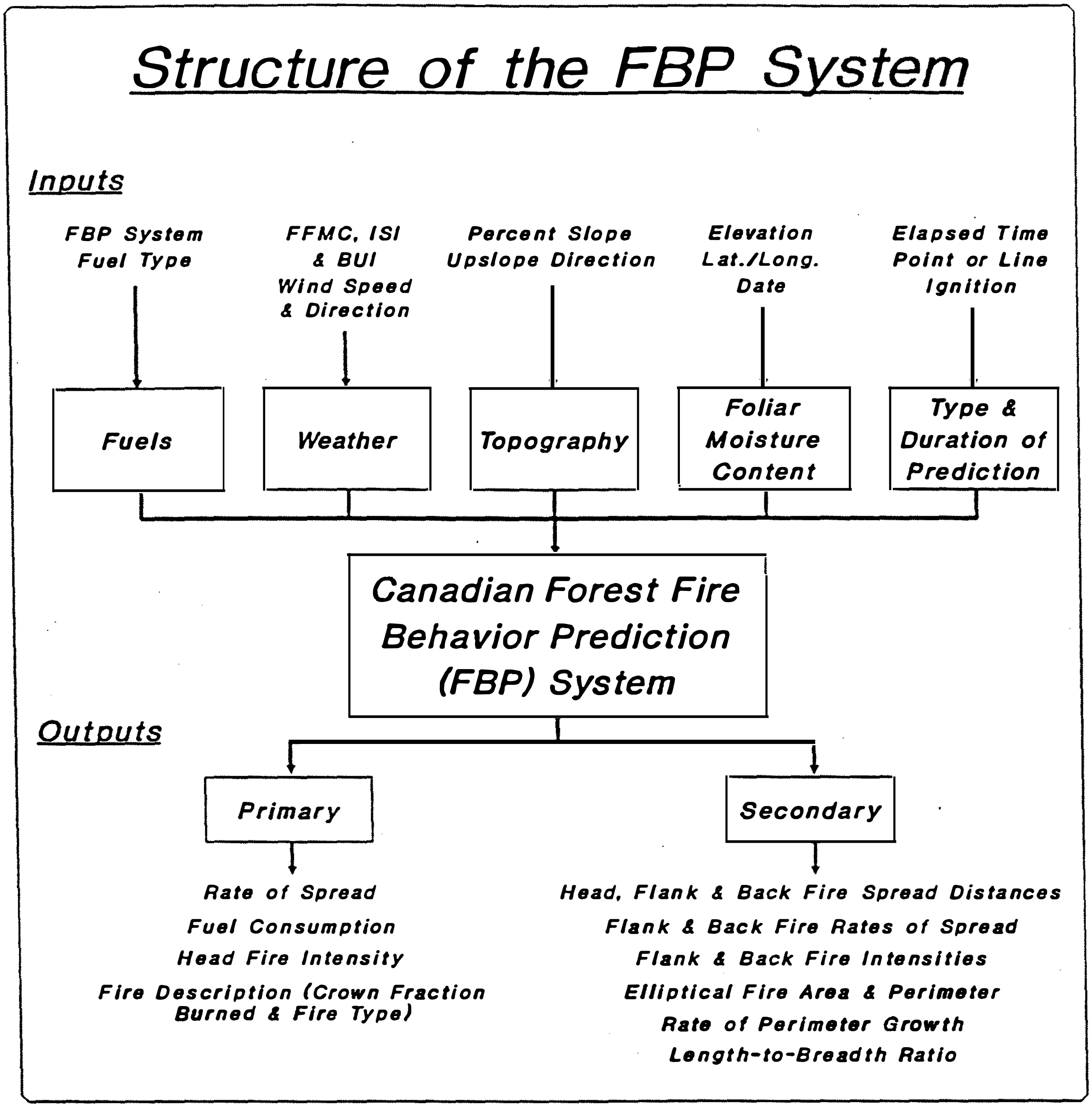

Figure 3. Structure of the Canadian Forest Fire Behavior Prediction (FBP) System.

(d) Foliar Moisture Content

The FMC influences calculations related to the prediction of crown fire involvement for coniferous and mixedwood fuel types. It also influences crown fire rate of spread in the Conifer Plantation (C-6) fuel type. The percent foliar moisture content (FMC) is computed using the latitude (°N), longitude (°W), elevation (m) above mean sea level, and the date. Within the FBP System the FMC can vary between 85% and 120%, with the minimum FMC usually occurring between mid-May and mid-June.

(e) Type and Duration of Prediction

The FBP System allows for two different types of fire behavior predictions depending on whether or not the fire has reached its equilibrium rate of spread. A point source prediction is used for a fire that is in its early stages of fire growth and is still accelerating. A prediction for

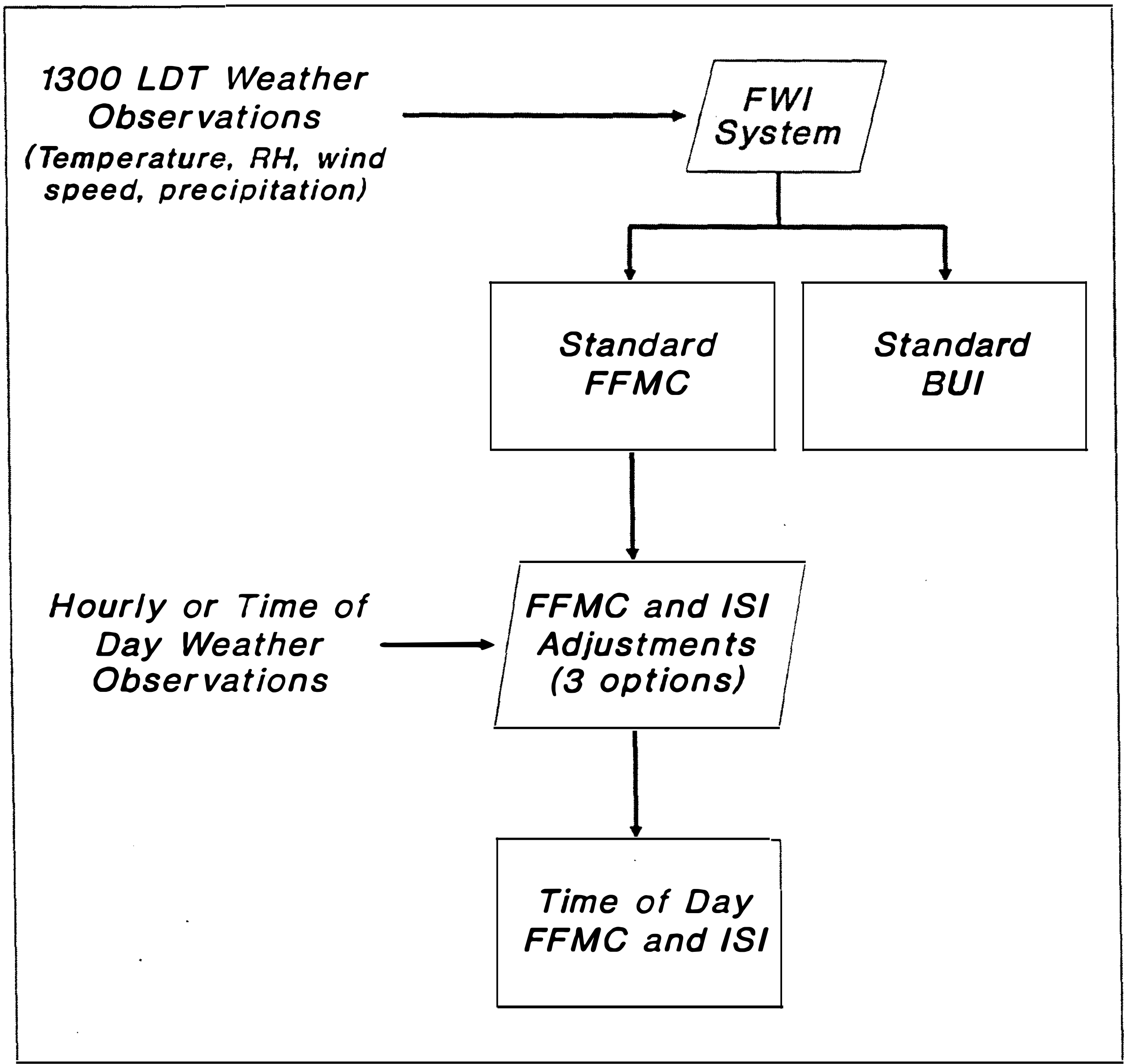

Figure 4. Weather inputs used in the FBP System

a line ignition fire is used when a fire has already reached its steady-state rate of spread. For example, a point source prediction would be used for a fire started from a match, campfire, lightning strike, or spot fire occurring a large distance ahead of a spreading fire. On the other hand, a line ignition prediction would be used when a wind shift occurs on a large fire causing the flank fire to become the head fire.

Duration of the prediction or the elapsed time (in minutes) determines the fire behavior characteristics of an accelerating fire starting from a point ignition. It is also necessary for the calculation of many of the fire size components of the secondary outputs.

Outputs

(a) Primary

Three of the four primary outputs in the FBP System (Figure 3) relate directly to Byram's fire intensity equation (Byram 1959). They are rate of spread (m/min), fuel consumption (kg/m^2), and head fire intensity (kW/m). The fourth primary output, fire description, has 3 categories: surface fire, intermittent crown fire, and continuous crown fire. They are defined by the degree of crown involvement or crown fraction burned (Table 2).

(b) Secondary

The 11 secondary outputs (Figure 3) are based on the assumption that a fire will grow in an elliptical shape if fuels, weather and topographic conditions remain relatively constant. The secondary outputs and their common units are:

- Head, flank and back fire spread distances (m),
- flank and back fire rates of spread (m/min),
- flank and back fire intensities (kW/m),
- elliptical fire area (ha),
- elliptical fire perimeter (m),
- rate of elliptical perimeter growth (m/min), and
- elliptical length-to-breadth ratio (fire shape).

PRINCIPAL CALCULATION PROCEDURES

To produce a fire behavior prediction the FBP System uses a variety of theoretical and empirical models. It is sufficiently complex that a computer is required in order for all of the FBP System outputs to be calculated. Therefore, understanding why and how a specific calculation is made is crucial to the effective use of the FBP System. A summary of the principal calculation procedures is given below and a more detailed discussion is provided in Forestry Canada Fire Danger Group (1992).

(a) Fire Site FFMC and ISI

The time of day adjusted FFMC and resulting ISI can be calculated using three different methods. Each method requires a different type and amount of information which affects the representativeness of the indexes.

(b) Rate of Spread (ROS)

The ROS is based on the fire site ISI value and can be adjusted for the steepness of a slope, the interaction between slope direction and wind direction, and increasing fuel availability as accounted for through the BUI.

(c) Fuel Consumption

The fuel consumption calculation includes both surface fuel (i.e., down woody and forest floor material) consumption and crown fuel consumption. Surface fuel consumption is based on the BUI for most fuel types, and crown fuel consumption is dependent on the crown fuel load (foliage only) and the degree of crown involvement.

Table 2. Fire description categories used in the FBP System.

Fire type	Crown fraction burned[a]
Surface fire	≤ 0.1
Intermittent crown fire	0.1-0.89
Continuous crown fire	≥ 0.9

[a] Crown Fraction Burned (CFB) refers to the proportion of tree crowns in a given area that are involved in the fire.

(d) Crown Fire Initiation

The FBP System uses Van Wagner's crown fire theory (Van Wagner 1977) to determine whether the crown fuel layer of a given coniferous or mixedwood stand will become involved in the fire. The theory states that there is a minimum or critical surface fire intensity value that must be exceeded for crowning to occur. Once crowning is initiated, a second assumption is made which assumes that complete crown involvement will occur when the critical surface fire rate of spread (which corresponds to the critical surface fire intensity) is exceeded by a value of 10 m/min.

(e) Fire Intensity

The FBP System predictions of fire intensity are modeled after Byram's (1959) fire intensity equation as follows:

$$\mathbf{I = 300 \times FC \times ROS} \qquad [1]$$

where I = fire intensity (kW/m),
FC = weight of fuel consumed per unit are in the active fire front (kg/m^2), and
ROS = rate of forward spread (m/min).

Note that the constant value of 300 is derived by dividing an assumed standard value of 18,000 kJ/kg for the low heat of combustion by 60, allowing ROS to be expressed in m/min rather than m/sec.

(f) Elliptical Fire Growth Model

A simple elliptical fire growth model is used to calculate most of the secondary outputs. For example, the prediction of the area or perimeter of a fire is simply the mathematical calculation of the area or perimeter of an ellipse.

(g) Acceleration of Point Source Fires

An acceleration period has been incorporated into fire growth projections for point source ignition fires to account for the time it takes such fires to reach their equilibrium rate of spread. For open-canopy fuel types it is assumed that a fire will achieve 90% of its equilibrium rate of spread after 20 minutes, whereas for a closed-canopy fuel type it will take between 20 and 75 minutes depending on the degree of crown involvement.

(h) Back Fire Rate of Spread

Back fire rate of spread is calculated from the wind speed and the head fire rate of spread and is independent of the length-to-breadth ratio.

(i) Grass Fuels Rate of Spread

The rate of spread in grass fuels is dependent on the degree of curing and the ISI. Grass fuels with less than 50% cured material are considered insufficient to support fire spread. Grass fuel load does not influence rate of spread but it does affect the amount of fuel consumption and therefore the fire intensity.

(j) Conifer Plantation Fuel Type

For the Conifer Plantation (C-6) fuel type, certain fire behavior characteristics, particularly rate of spread, are modeled using a physically-based rather than an empirical model (Van Wagner 1989). A rigorous dual-equation model that predicts rate of spread as a value between two bounding curves for surface fires and crown fires was developed for the typically homogeneous conifer plantation fuel type, whereas a single-equation regression model was used for the other, more variable fuel types.

OPERATIONAL USES OF THE FBP SYSTEM

The FBP System is currently being used for two primary operational activities. First, it is used by many fire management agencies in Canada for the prediction of large fire behavior. For example, fire behavior officers will often attempt to predict the rate of spread of a campaign fire, its shape and the fire intensity at different points on the perimeter so that an overhead team can develop appropriate fire suppression strategies. Second, the FBP System is used in preparedness planning systems that allow fire managers to pre-position their fire suppression resources based on the potential fire behavior. The FBP System is often an integral part of this planning process regardless of whether the preparedness system is a complex computerized fire management system (Lee and Anderson 1991; Kourtz 1984) or a more simplified manual preparedness system (Lanoville and Mawdesly 1990; De Groot 1990; Hirsch 1991).

In the future it is expected that the FBP System will also be related to other aspects of fire and resource management. For example, a strong relationship may exist between certain fire behavior characteristics (e.g., fire intensity, rate of perimeter growth, etc.) and the effectiveness of various types of fire suppression equipment and methods. Also, it may be possible to directly correlate specific fire behavior parameters to post-fire vegetative responses or certain types of environmental impacts such as smoke emissions.

CONCLUDING REMARKS

The FBP System is a systematic method for assessing fire behavior in Canada that integrates many of the major factors that are known to influence fire behavior. It is a complex, mathematical system that can be utilized by fire managers in their decision-making process. However, like any other system that attempts to simulate what occurs in the "real world", the FBP System has its limitations. For this reason, individuals that use the FBP System must not only be familiar with its inputs and outputs but they must be aware of how the system derives fire behavior predictions.

To predict fire behavior accurately requires a great deal of skill and knowledge. It is heavily dependent upon an individual's experience and their understanding of the basic principles of fire behavior. Since no model or system could ever account for all the variables that could affect a fire's behavior, the fire manager must still rely on his or her own ability to cope with unique and unusual situations. Thus, the best possible fire behavior predictions are those that are based on the systematically calculated values of the FBP System in combination with the opinions and assessments of experienced fire management personnel.

ACKNOWLEDGMENTS

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Western Region Technical Notes

91-N-104

Drought Code Calculations in the Yukon: An Overview and Experimentation with Different Procedures [1] [2]

by

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November 1991

Abstract

Because of the Yukon's dry climate, over-wintering the Drought Code for use in Yukon Forest Service operations has been proved to be a problem. In the past, there were concerns that using the actual winter precipitation would result in unrealistically high start-up values for the Drought Code, so a different procedure was used; one which involved the percent-of-normal precipitation values. This paper summarizes a series of tests that were conducted on actual Yukon data to measure the effect of using different procedures to over-winter the Drought Code. It is suggested that using the actual precipitation amounts would probably not result in significant problems, and that consideration be given to using the actual precipitation amounts in the future.

Résumé

Dû au climat très sec du Yukon, la planification hivernale du Code de Sécheresse, pour une utilisation opérationnelle au Service de la Foresterie du Yukon, a toujours été un problème. Auparavant, l'intérêt était que l'utilisation des précipitations hivernales actuelles résulteraient en une initialisation irréaliste du code de sécheresse. Alors une approche différente fut utilisée, dont l'une impliquant les valeurs du pourcentage de précipitation normale. Ce document dresse un bilan des séries de tests qui ont été menées sur les données actuelles du Yukon pour mesurer l'effet de l'utilisation de différentes approches pour la planification hivernale du code de sécheresse. Il a été suggéré qu'en utilisant les quantités actuelles des précipitations ne devraient probablement pas créer de problèmes significatifs, et ces considérations seront données pour utiliser les quantités de précipitation actuelles dans le futur.

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[1]A paper presented at the Sixth Western Region Fire Weather Committee Scientific and Technical Seminar, March 23, 1992, Edmonton, Alberta.

[2]Reprinted with permission of the Atmospheric Environment Service, Western Region.

[3]The author was the ODIT/Forestry Meteorologist at the Yukon Weather Centre until November 1990.

1 Introduction

The Yukon Weather Centre (YWC) is responsible for calculating the components of the Fire Weather Index (FWI) system in support of the Yukon Forest Service's (YFS) operations. This includes calculating the start-up Drought Codes each spring. The procedure for doing this calculation always has presented difficulties, mainly due to the lack of precipitation in Yukon, and a variety of approaches have been used over the years.

The report discusses some of these problems in detail, and presents the results of using some different procedures. Some familiarity with the Canadian Forest Fire Danger Rating System (CFFDRS) and one of its sub-systems, the Fire Weather Index (FWI) System, is assumed; a more detailed explanation is available elsewhere; e.g. Turner and Lawson (1978) or Van Wagner (1987).

2 The Drought Code

The Drought Code (DC) is one of the three fuel moisture codes which comprise the FWI System—the Fine Fuel Moisture Code (FFMC) and the Duff Moisture Code (DMC) being the other two. It models the ground water reservoir, or deep organic forest soil moisture, roughly the layer between 10 and 25 cm below ground level. It is also related to the moisture content of large downed wood and the availability of water in streams and swamps (Van Wagner 1987). The Drought Code is related to the inverse log of the soil moisture equivalent (Q) by:

$$DC=400\times\ln\left(\frac{800}{Q}\right) \qquad (1)$$

The soil moisture can vary between about 50 (almost totally dry) and 800 units (totally saturated); thus the corresponding Drought Code scale runs roughly between 1000 and 0 units.

During the summer, the Drought Code changes daily as a result of moisture gains (rain percolating down through the soil layers) and losses (evaporation from the surface and transpiration from vegetation). When there has no precipitation during the past day, the DC is related to the previous day's value (DC_o) by:

$$DC=DC_o+0.5(0.36(T_{noon}+2.8)+L_f)) \qquad (2)$$

where T_{noon} is the local noon temperature (°C) and L_f is the length of day factor. Depending on the time of year, the DC typically increases by about 5 to 7 units for each day without precipitation. Note that a linear increase in DC implies an exponential decrease in the soil moisture equivalent; i.e. wetter soils dry faster than dry ones.

When there has been at least 2.9 mm of precipitation (anything less is assumed to be intercepted before it can filter downwards), the DC_o is first adjusted by adding a percentage of the precipitation to the fuel moisture equivalent (Q_o), then converting it back to a Drought Code:

$$Q=Q_o+3.94(0.83r_{24}-1.27) \qquad (3)$$

where r_{24} is the 24-hour precipitation (in mm) recorded up to local noon.

Rain quickly reduces the Drought Code, even small amounts. Using a value of 600 units for the DC (a typical mid-summer value), 5 mm of rain will reduce it by about 20 units; 10 mm by 55 units; and 20 mm by over 110 units. Also note that for the same amount of rain, a high DC will drop more than a low one will, because of the logarithmic relationship to the soil moisture.

Overall, the Drought Code slowly rises throughout the summer; i.e. the amount of precipitation is not enough to balance the moisture lost through evaporation and transpiration, and the soil is in a net moisture deficit. The DC typically peaks at about 500 to 600 units during a dry, warm summer, and can reach 1000 in very dry and hot climates. In Yukon, this peak usually is in the late summer (the end of August or early September). The DC then drops slightly during the cool, rainy weather of late September and October.

3 Over-wintering the Drought Code

In the original FWI System, the ground was assumed to be totally saturated when it thawed in the spring; i.e. the presumption was that the over-winter precipitation replenished all the moisture. The normal procedure was to start the spring with a DC of 15, three days after the snow disappeared.

This assumption works well for a wet climate such as along the British Columbia coast or in Eastern Canada. However, it is less valid for drier ones; for example, such as in the interior of BC or in northern Canada. In these areas, the over-winter precipitation is not sufficient to replenish the soil moisture and the soil is not totally saturated in the spring. To overcome this problem, Turner and Lawson (1978) developed a procedure for over-wintering the DC, and this now forms an integral part of the FWI System.

In this procedure, the daily DC calculations are continued until ground freeze-up, then the winter precipitation is added to its soil moisture equivalent to estimate the spring moisture value:

$$Q_{spring}=aQ_{fall}+b(3.94r_{winter}) \quad (4)$$

where r_{winter} is the over-winter precipitation (in mm), a is the Carry-Over fraction (COF), and b is the Precipitation Effectiveness Fraction (PEF). The spring DC is then obtained from equation (1).

There are two estimates of the effectiveness of the winter snow to replenish the soil. The COF represents the fraction of the fall's moisture that will be carried over to the following spring. It varies between 0.00 and 1.00. When the FWI computations are not carried right up to the freeze-up date, or in areas that experience chinooks, values of 0.75 or 0.90 are recommended for the COF.

The PEF estimates the fraction of winter snow that will remain on the ground till spring, when it will melt and percolate into the soil. Some of the snow will sublimate during the winter, and some of the melting snow will evaporate or run-off the frozen ground. The value used for the PEF depends on the type of soil, the depth and degree of ground frost, and (again) whether chinook conditions exist. Values between 0.50 and 0.75 are suggested for climates such as Yukon's.

4 Drought Code calculations in Yukon: a historical perspective

Using typical values (0.75 for both the COF and PEF, and a fall DC of 600), about 200 mm of winter precipitation are required to reset the DC to 15 for the following spring. But Yukon's climate is very dry, and much of the territory seldom receives 200 mm of precipitation during a wet winter, never mind during an average one! Figure 1, taken from Wahl (1987), shows the annual Yukon precipitation pattern. The average precipitation varies from a minimum of about 250 mm (in the rain shadow to the lee of the St. Elias Mountains in southwestern Yukon, and to the lee of the Pelly Mountains) to a maximum near 700 mm (through the Pelly-Cassiar Mountains). The winter portion of the annual precipitation (not shown), or roughly between October and March, is as low as 60 mm in places. The summer precipitation is mostly convective in nature, with most of the daily amounts less than 5 mm—which are too low to have much of an effect on the Drought Code.

Figure 2 shows the mean monthly precipitation values for Whitehorse, one of the driest Yukon stations. Note the precipitation maximum in the late summer (July and August) and the minimum in the early spring (around April). This distribution is typical of Yukon stations. The actual precipitation varies from year to year, of course. Figure 3 shows the over-winter precipitation for Whitehorse for the past 10 years. It varied between 60 mm and 135 mm, with a mean of 103 mm.

Thus, if the procedure for over-wintering the DC was strictly followed, the spring DCs for many Yukon stations would not be reset to 15, and some would be much higher. In the past, this gave rise to several concerns:

- A higher spring DC would result in a higher fall DC, which, in turn, would result in an even higher spring DC the following year. The spring and fall DCs would keep rising, eventually oscillating around some much higher value (the value of which was unknown).

- As some of the components of the FWI System—e.g. the Build-Up Index (BUI), the Fire Weather Index (FWI), and the Daily Severity Rating (DSR)—are (weakly) dependant on the Drought Code, they too would increase. This would be especially true in the spring, when they would start at much higher values.

- The Drought Codes and indices would not be representative of fires that develop, which is one of their main applications. The DC, being a measure of the dryness of the deep layers, is useful in estimating the fuel (energy) available to a fire, the potential for sub-surface fires, and ground-water available for suppression activities. The concern also was that the concept of modelling the moisture in a deep duff layer was not as useful in an area such as the Yukon, where the soil structure is quite different than one in a wet southern climate.

- At the Yukon borders, the FWI indices would not match those done in other jurisdictions, especially in British Columbia.

Because of these concerns, the spring Drought Codes for Yukon have intentionally been adjusted downward over the years. The procedure involved using a "percent-of-normal" precipitation amount. In equation (4), r_{winter} was first adjusted by:

$$r_{winter'} = 200\left(\frac{r_{winter}}{r_{normal}}\right) \quad (5)$$

where r_{normal} is the average over-winter precipitation.

Using this modified procedure, if the over-winter precipitation was near (or above) its normal value—no matter *how* low this normal was—then the spring DC would be 15. With less precipitation, the spring DC would still be reset to 15 if the fall DC was low. Thus this method generally resulted in much lower DCs, even for very dry locations.

Table 1 shows the calculations for the 1990 spring start-up Drought Codes for various Yukon stations. There are two sets of spring DCs shown, one using the original method with the actual precipitation (the "Oct-Mar Pcpn," "Apr Pcpn," and "Sprg DC1" columns), and the other using the revised procedure, with the percent-of-normal precipitation (the "Norm Pcpn," "Perc Norm," and "Sprg DC2" columns). A value of 1.00 was used for the COF and 0.90 for the PEF. As discussed earlier, these values are too high, but they were the ones used by the YWC for the past few years. The two methods result in significantly different spring Drought Codes. Due to a wetter-than-normal winter over most of Yukon, the modified DCs are all 15. But using the actual winter precipitation, many of the spring DCs are higher than 100, and some are over 200.

Over the past couple of years, some concerns were raised about the validity of this revised procedure. Some felt that the lower codes, and the lower indices that they resulted in, did not match the measurements taken of deep soil moisture, nor with the characteristics of spring fires they were fighting. Van Wagner (1985) raised the point that normality is not a valid concept when dealing with drought indices; i.e. dry areas do get more fires (and more severe ones) than wet areas. A few years ago, the British Columbia Forest Service (BCFS), which also had been using a version of this revised procedure, went back to using the actual precipitation.

5 Effect of over-winter calculations on Whitehorse Drought Codes

It was decided to test the validity of the original concerns. Past studies (e.g. Alexander and Kreiborn (1983) and Alexander (1982)) have tested various Drought Code calculation procedures for other dry regions, including the Northwest Territories, but the author is not aware of any detailed studies using Yukon data.

Whitehorse data was used for the first test. With an average of 105 mm of precipitation from October 1 through April 30, it is not the driest winter area (the Burwash-Braeburn-Carmacks triangle and Ross River area are). Neither is it the driest summer station, as Old Crow, Carcross, and Haines Junction all normally receive less than Whitehorse's 150 mm. However, Whitehorse is one of the driest stations over the entire year and a long historical database is available.

Table 1. 1990 spring Drought Code start-up values for various Yukon stations, using actual precipitation and percent-of-normal precipitation procedures. The COF was 1.00 and PEF was 0.90.

Station	Fall DC	Date	Oct-Mar Pcpn	Apr Pcpn	Sprg DC1	Norm Pcpn	Perc Norm	Sprg DC2
Beaver Creek	435	Oct 01	77	2	153	115	67%	15
Braeburn	601	Oct 09	81	0	205	100	81%	15
Burwash	652	Oct 01	76	17	239	92	83%	15
Carcross			270	2	15	91	297%	15
Carmacks	680	Sep 26	125	6	99	89	140%	15
Cassiar			483	11	15	400	121%	15
Dawson	642	Oct 01	130	2	79	146	89%	15
Dease Lake	314	Oct 01	251	8	15	170	148%	15
Faro	570	Oct 01	145	5	29	127	114%	15
Haines Junc	625	Sep 26	195	13	15	143	136%	15
Hesselberg	381	Sep 30	200	15	15	200	100%	15
Henderson	476	Oct 02	140	3	15	140	100%	15
Mayo	620	Oct 01	105	0	138	126	83%	15
Old Crow	591	Oct 01	101	3	141	96	105%	15
Pelly Farm	582	Aug 31	120	2	89	120	100%	15
Ross River	719	Oct 01	108	5	154	107	101%	15
Swift River			389	15	15	314	124%	15
Teslin	410	Oct 01	158	15	15	157	101%	15
Tuchitua			206	17	15	336	61%	15
Watson Lake	452	Oct 01	149	6	15	173	86%	15
Whitehorse	584	Oct 01	125	2	77	105	119%	15

Table 2 contains Drought Code values for Whitehorse for the past 10 years, using four different methods of over-wintering the Drought Code. Figure 4 displays the same data in graphical form. For simplicity, only the spring start-up and the end-of-season fall Drought Codes are shown. It is important to keep in mind that the DCs normally reach a maximum during the late summer, one which can be significantly higher than the final fall code shown.

The spring start-up dates were the ones used in the past 10 years, and closely follow the definition (i.e. three days after the snow has disappeared). September 30 was used to mark the end of summer. The Whitehorse freeze-up usually comes a little later (typically mid to late-October) but this should not affect the results much, and was partially compensated for by adjusting the COF value. The over-winter precipitation was for the period of October 1 to April 30; this does not match the start-up date exactly, but as Whitehorse is so dry in April, this should not affect the numbers significantly.

Method #1, the first set of DC values in Table 2 (and the first line in Figure 4) shows the evolution of the Drought Code over the 10-year period, using a spring start-up value of 15, no matter how much over-winter precipitation there was. In this scenario, most of the final fall DCs range from 400 to 500. During dry summers (e.g. 1981 and 1989), the fall DCs end up over 550, while during wet summers (e.g. 1986 and 1988) they finish in the 250 to 350 range.

The second method incorporates the spring start-up DCs that were actually used by the YWC. During the early 1980s, when winter precipitation was lower than normal, higher-than-normal spring DCs were common. After peaking at about 175 in 1984, the spring DCs then dropped, due to two reasons: (1) there were several consecutive summers and winters with above-normal precipitation; and (2) the spring DCs were being modified downward, using the percentage of normal precipitation procedure described above. The spring DC was above 15 for the past few springs, a reflection of dry winters.

Method #3 uses the actual over-winter precipitation. Here, a value of 1.00 was used for the COF and 0.90 for the PEF; again, these values are too high but are close to the ones that have been used. Note the gradual increase of the spring DC value through the early 1980s. Using 15 as the starting value in 1981, it gradually increases to 148 in 1983 and reaches a maximum of 215 in 1984. The next three springs would have had DCs near the normal value of 15, but they rise again for the next three years. Using this procedure, the highest spring DC would have been 222, in 1988.

Table 2. Calculation of Whitehorse Drought Codes over a 10-year period, using 4 different methods (explained in the text).

Year	Spring start-up date	Fall end date	Over-winter Pcpn	Method #1 Spring DC	Method #1 Fall DC	Method #2 Spring DC	Method #2 Fall DC	Method #3 Spring DC	Method #3 Fall DC	Method #4 Spring DC	Method #4 Fall DC
1980	0425	0930	84	15	412	15	412	15	412	12	412
1981	0426	0930	138	15	553	15	553	15	553	101	594
1982	0426	0930	122	15	482	90	511	77	509	192	545
1983	0422	0930	89	15	416	115	451	148	460	260	490
1984	0415	0930	61	15	505	175	567	215	580	324	613
1985	0506	0930	134	15	508	15	508	54	532	167	584
1986	0507	0930	121	15	243	15	243	72	260	190	286
1987	0401	0930	92	15	503	15	503	33	511	140	552
1988	0416	0930	66	15	355	100	380	222	409	336	431
1989	0420	0930	96	15	567	50	583	90	599	197	637
1990	0420		128	15		50		75		189	

It is important to emphasize here that although the spring DC often was significantly higher than 15, the resultant fall DC did not increase as much. It generally was within 50 units of the values obtained in the methods, with a maximum difference of 75 (in 1984). As explained earlier, there are two reasons for this. The first is that the Drought Code is related to the inverse log of the soil moisture equivalent, and as precipitation amounts are *additive* to the moisture equivalent, the Drought Code will drop only *logarithmically*. The second reason is that the drop in soil moisture by evaporation is exponential, thus moist soils will dry out more quickly than dry ones (though the DC rise is linear).

The result is that only a small fraction of the original difference in spring Drought Codes will persist through the summer. For most stations, the different start-up values quickly converge after some heavy summer rains. For dry stations a significant difference might persist through the summer.

Also, it would seem that the spring and fall Drought Codes would *not* keep rising. Though the DC started at a high value (215) in the spring of 1984 and climbed to final value of 580 in the fall, the wet winter that followed would have knocked the spring DC in 1985 back to only 54.

The final step ("Method #4") presents the other extreme. The actual precipitation again was used, but with values of 0.75 for both the PEF and COF. This results in even higher spring DCs. The steady rise in spring start-up values in the early 1980s is now even more pronounced, with the spring DC peaking at 324 in 1984. The next three wet years again dampen the spring DCs, but only down into the 140 to 190 range. They rise again during 1987-90, reaching a high of 336 in 1988, before slipping back to around the 200 mark for the past two springs. Again, note that starting with spring DCs hundreds of units higher than 15, the fall DCs didn't change much. The highest difference was in 1984, at 110 units.

So it seems as if the first concern may be unfounded. The DC for Whitehorse may cycle between slightly higher values, but it doesn't keep on increasing, nor is this value extremely high. Even using the most pessimistic procedures and the driest weather, it seems that typical spring DCs (for Whitehorse) would hover in the 100 to 200 range, with occasional excursions in the 300s (following several consecutive dry summers and winters).

6 Further tests with Drought Codes using other stations

But what about other stations—would their increases in DCs be more pronounced? Ross River, for example, normally is much drier in the summer than Whitehorse and thus has higher fall DCs. Using an initial spring DC of 15, the final fall DC in 1981 was 733. What kind of Drought Codes might result there if higher spring codes were allowed? The next two tests tried to estimate the maximum Drought Codes that might be encountered in Yukon.

Figure 5 relates the spring DC to the amount of over-winter precipitation, using a PEF of 0.75. Several different combinations of fall Drought Codes and COF values are used. The most pessimistic one is a fall DC of 900 combined with a COF of 0.75, which probably is close to the extreme. Note how quickly the Drought Codes drop as the precipitation increases or the COF value rises. The lowest Yukon average winter precipitation amounts (in the Burwash and Ross River areas) are around 80 mm, which under these starting conditions would result in spring Dcs between 250 and 400. The record low values amounts would likely be about half this amount, which could conceivably create spring DCs as high as 600 (following a dry summer).

Figure 6 shows the influence of the spring DC on the final fall value. The Ross River summer of 1981 was used here. With about 60 mm of rain, it was one of the driest summers recently recorded in Yukon. Using spring start-up DCs ranging from 15 to 615, the resulting fall DCs range from 733 to 1077. Thus a difference of 600 units in the spring DC would have resulted in a difference of 344 units in the fall; i.e. 57% of the initial difference would persist through the summer.

However, to fully understand what is happening, one must also consider how the soil moisture is evolving. In the "wet" case, a Drought Code of 15 corresponds to a moisture equivalent of 771 units, and a DC of 733 converts to 128 moisture units. This is a drop of 642 units in the soil moisture equivalent during the summer. In the "dry" case, the soil moisture equivalent starts at only 172 moisture units and drops to 54 units by the end of the summer, a change of only 118. The difference between the two final moisture values is 74 units, much less than the spring differences. The reason? Though both scenarios have the same moisture gain (through precipitation) during the summer, the evaporational loss is exponential. The wetter soil loses its moisture at a faster rate.

In summary, the extreme scenario would likely see the Drought Code cycling between a spring value of about 600 and a fall value of over 1000. But this would require some very unusual weather: several consecutive hot, dry summers combined with very dry winters. However, these high Drought Codes would still not persist forever. Even one wet winter (e.g. 150 mm of rain) would be enough to reduce even the highest fall DC down to near 200 units the following spring, and the cycle would start all over again.

7 Analyzing the effects of higher spring DCs on FWI indices and ratings

The next step was to examine the influence that higher spring DCs would have on the fire weather indices. The dry, warm summer of 1989 of Whitehorse was used here (it was similar to Ross River's 1981 season). Print-outs (not included) of all the indices for the entire season were produced, the first using a spring DC of 15 (the "wet" scenario) and the second using a spring DC of 315 (the "dry" case).

The initial Drought Code difference of 300 units persisted until June 14, when 8.8 mm of rain fell. Up to that point, the higher spring DCs did result in a few significantly higher values for the various indices. The BUI (which is heavily influenced by the DC value) for the "dry" case started off in the 50 to 60 range, or about 20 to 30 units higher than in the "wet" case (roughly 100% higher). By mid-June, it was around 140. The difference was still 35 units, but only now 40 to 50% higher.

The FWI normally fluctuates more day-to-day than do some of the other indices, as it is more heavily influenced by other weather parameters (such as the wind speed). Here, whenever the "wet" case had an FWI in the 5 to 10 range, the "dry" case's was 2 or 3 units higher. When it was in the 11 to 20 range, the dry case's was about 4 units higher, and when it was in the 20s, it was about 5 units higher. This latter figure represents an increase of between 20 and 30%, or about one category in Yukon's fire danger classification system (e.g. from "High" to "Very High"). In terms of fire behaviour (Turner and Lawson, 1978), this is considered significant. The DSR, which is basically an exponential of the FWI, did not change much. Usually less than 10 units, it typically increased by about 2 to 3 units under the "dry" scenario.

After some significant rainfalls in mid-June, the BUIs for the two scenarios were almost equal; i.e. the rain had effectively reset them both. The FWIs and DSRs differed by only 1 or 2 units—even though the two Drought Codes were still 200 units different! When the dry case DC reached its peak of 800 at the end of August, there were no significant differences in any of the indices.

Thus, though the Drought Codes may be significantly different—which may be important to operations—the indices which depend on the DC appear not to change much. This result perhaps is to be expected, as the FWI System was set up that way in the first place.

There was one more concern to address: that these higher DCs might not be representative of the fires (i.e. their intensity, and growth) that develop in Yukon, especially in the spring. This relationship can only be studied by examining actual fire behaviour.

8 Conclusions

It appears that the concerns regarding the over-wintering of the Yukon Drought Code may be unfounded. Though using the actual over-winter precipitation and lower COF and PEF values would result in higher spring Drought Codes (typically in the 100 to 200 range, and occasionally as high as 500), and higher fall codes (perhaps as high as 1000), these Drought Codes would not continue to grow in time. Neither would these higher spring DCs result in very many significant increases in the fire weather indices.

If the suggested fire behaviour studies show that these higher Drought Codes are not unrepresentative of fires that develop in Yukon—especially those during the early summer—then it is recommended that the actual over-winter precipitation be used in calculating spring start-up Drought Codes in Yukon. This would bring Yukon's procedures in line with that of the BCFS. If this is done, then the DCs for all Yukon stations should be recalculated for the past 2 or 3 years to provide a suitable run-up period for the 1991 forest fire season.

Acknowledgements

The author would like to thank Bruce Lawson of the Fire Research Unit of the Pacific and Yukon Region of Forestry Canada for his valuable comments and suggestions.

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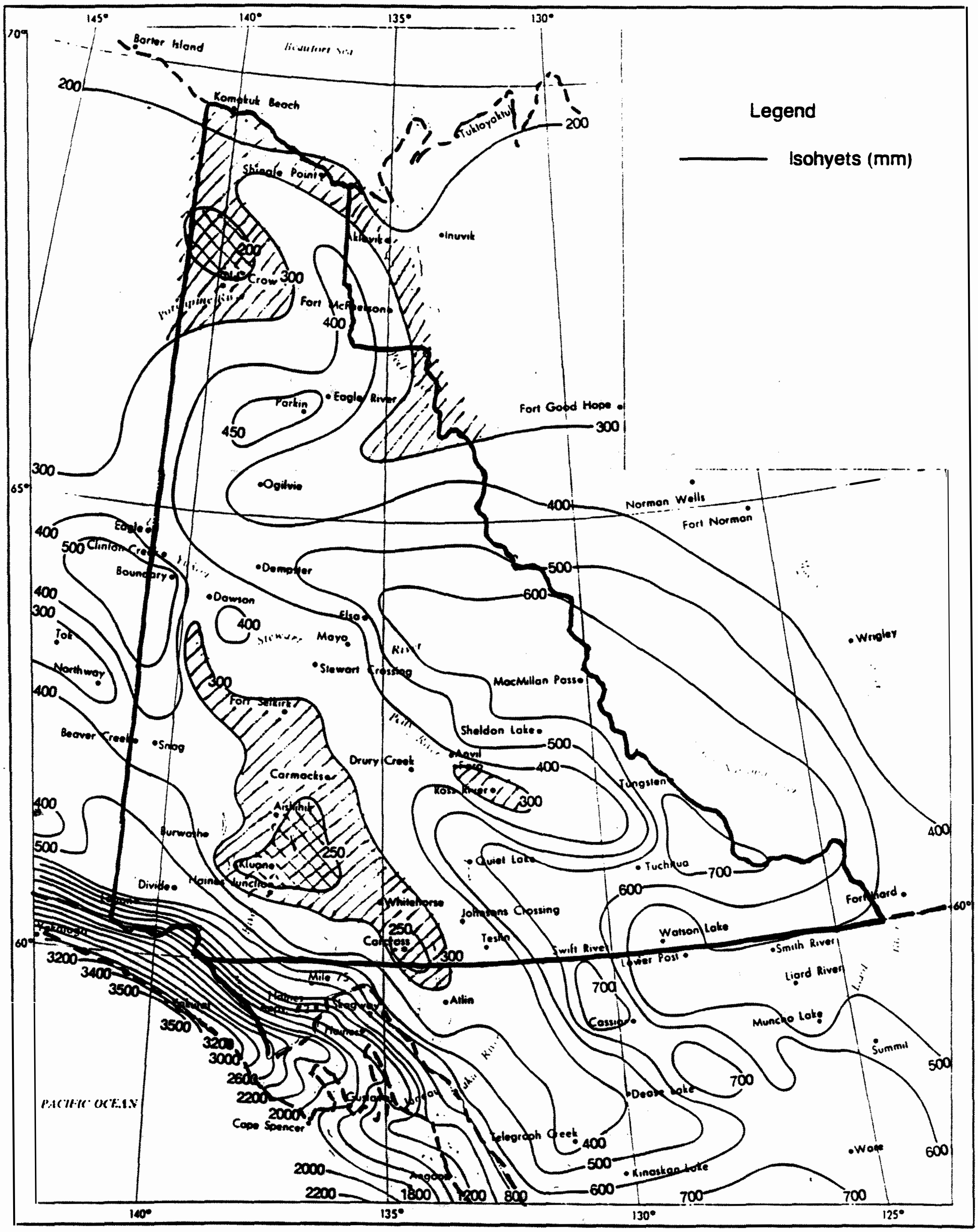
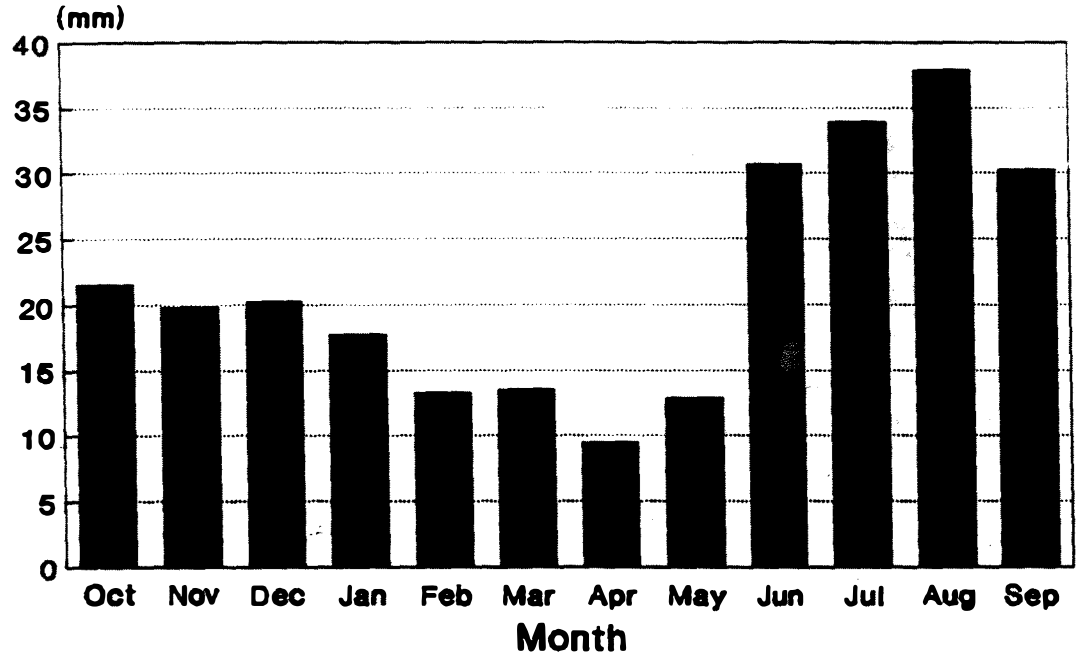


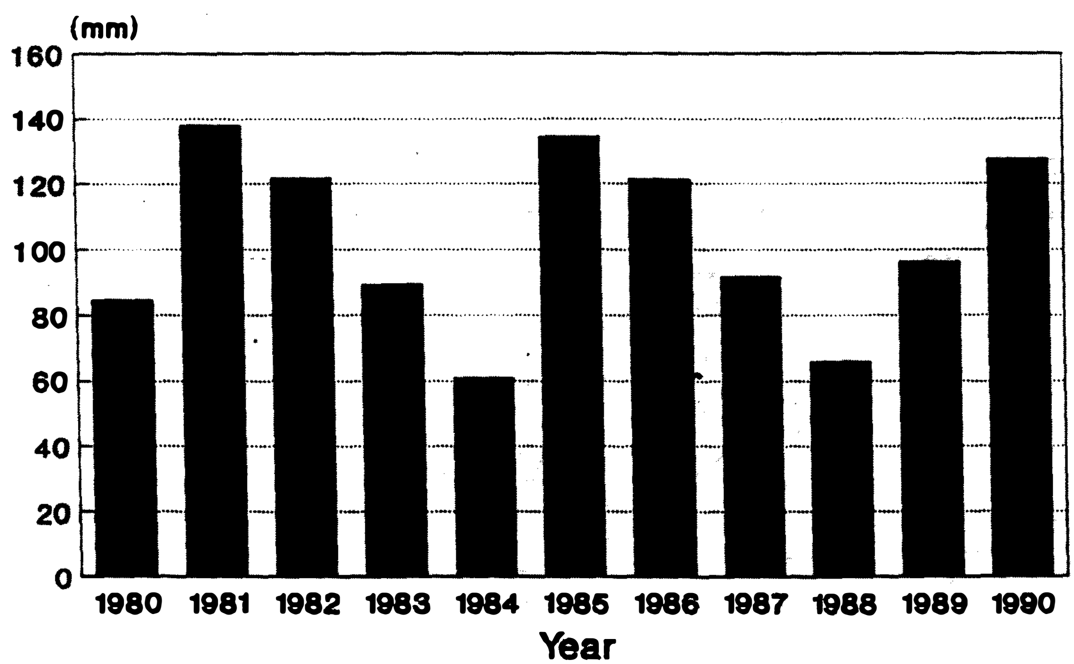
Figure 1 Mean annual precipitation for Yukon, taken from Wahl (1987).

Figure 2. Monthly mean precipitation
Whitehorse



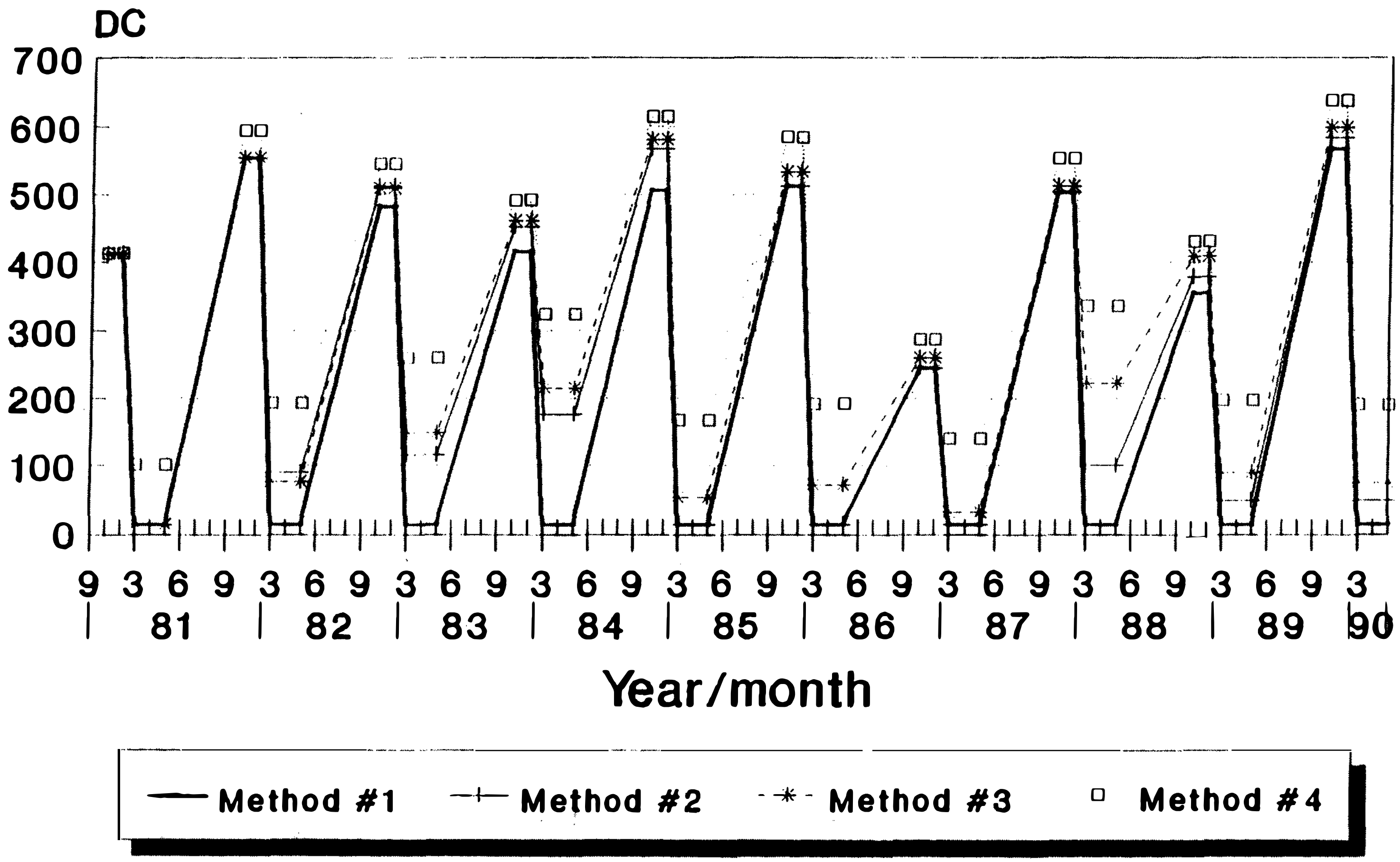
Based on 1951-80 data

Figure 3. Over-winter precipitation
Whitehorse



October (previous year) to April

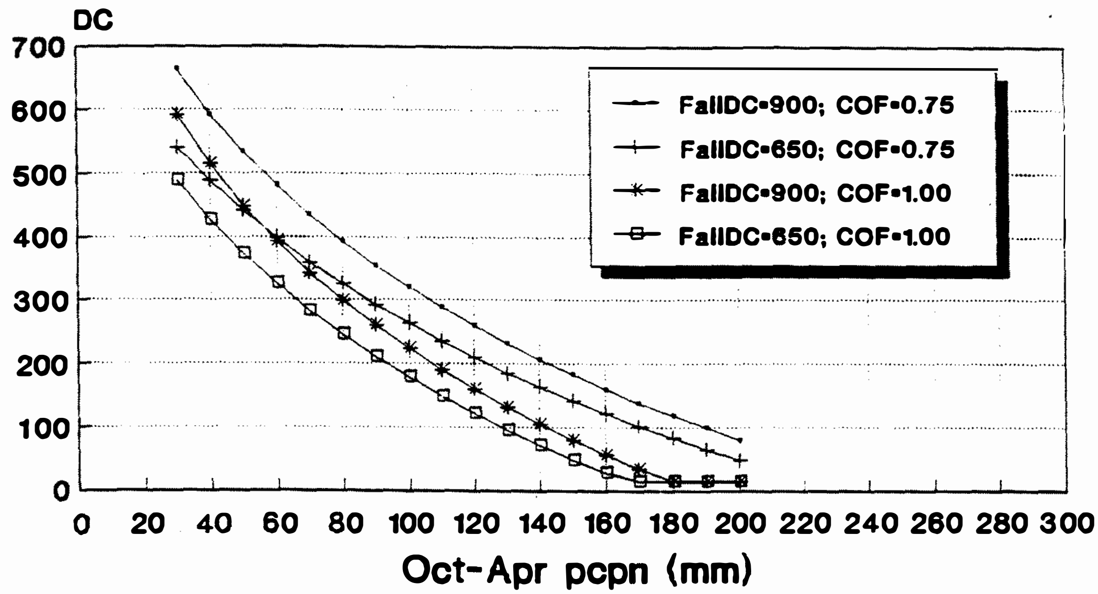
Figure 4. Whitehorse Drought Codes
Dependence on over-winter calculations



Methods are explained in the text

Figure 5. Spring Drought codes

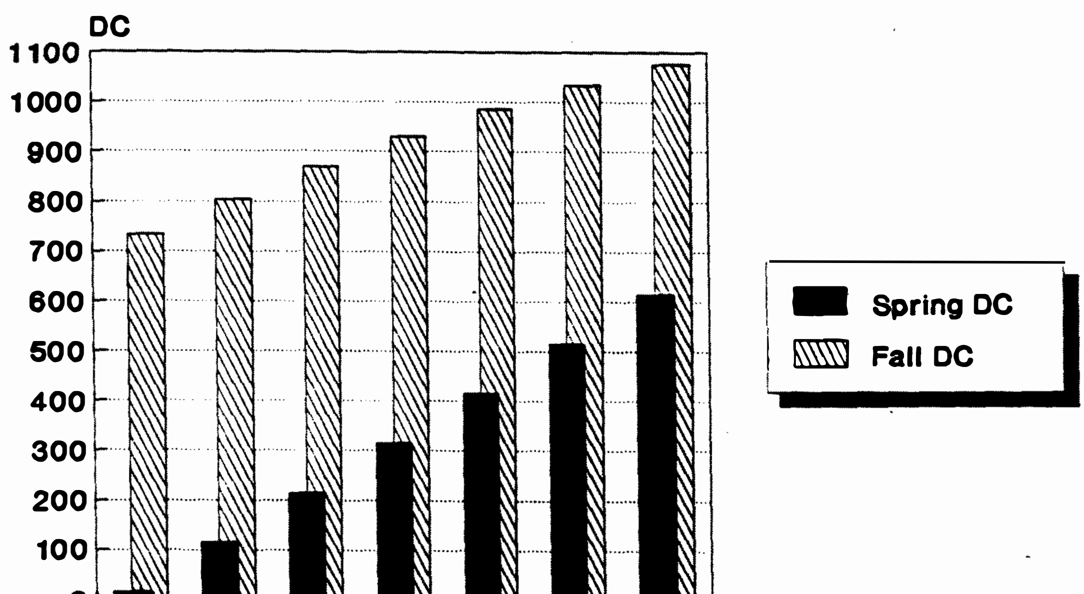
Dependence on fall drought code, over-winter pcpn, and COF



Using PEF=0.75

Figure 6. Fall Drought Codes

Dependence on spring start-up values



Using 1981 data from Rose River

LIGHTNING-CAUSED FIRE OCCURRENCES: AN OVERVIEW[1]

by Kerry Anderson[2]

ABSTRACT

Lightning-caused forest fires are a major problem in Canada. Igniting 34% of the nearly 10,000 annual fire occurrences in Canada (1973-1982), lightning-caused fires account for 87% of the total area burned. The Fuquay model has been generally accepted as a good representation of the lightning-caused forest fire ignition environment. This paper reviews this model and outlines the current understanding of each predictor parameter.

INTRODUCTION

Lightning is a major cause of fire occurrence and loss in Canada. According to statistics compiled from 1973 to 1982 (Ramsey and Higgins 1986), lightning caused 34% of the nearly 10,000 fires that occurred annually in Canada. Yet, these fires accounted for 87% (1,840,822 ha) of the total area burned nationwide each year. The reason for the disparity in proportions is that most lightning-caused fires occur in remote areas. This results in longer detection times and when fire fighting resources do arrive the fires are large, increasing the difficulty of containment and likelihood of escape. Also, dispatched resources must be transported by air increasing the costs to contain these fires.

Because of their nature, lightning-caused fires occur in almost random locations and numerous quantities, which can strain fire fighting attempts. During the 1981 fire season in Alberta, 165 fires were started between August 10 and August 20 by lightning. By August 20, 6 fires were still out-of-control and area burned was more that 52,000 ha (Nimchuk 1983). In Manitoba, lightning ignited 175 fires between July 18 and July 20, 1989. As burning conditions worsened, fires that were still out-of-control burned 508,000 ha (Hirsch 1991). On August 9 and 10, 1990 in the Lac la Biche Forest of Alberta, a single lightning storm was responsible for 134 reported fires in a 24 hour period (B. Bereska pers. com.).

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[1]A paper presented at the Sixth Western Region Fire Weather Committee Scientific and Technical Seminar, March 23, 1992, Edmonton, Alberta.

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THE PHYSICAL PROCESS

The physical process behind lightning-caused fire occurrences has been the subject of study for some years. In 1979, Fuquay *et al.* layed out a framework that has been generally accepted by the research community (Latham 1979; Kourtz and Todd 1992).

The lightning-caused fire occurrence can be broken down into three distinct stages: ignition, survival, and arrival.

Ignition

The ignition phase of lightning-caused fire occurrences can be defined as the process in which a smouldering fire is started in the forest fuels. By definition, a lightning-caused forest fire is initiated by a cloud-to-ground lightning flash. Yet, not all lightning flashes that hit trees ignite fires. The likelihood of a lightning flash triggering an ignition is determined by the characteristics of the lightning flash, fuel conditions, and precipitation.

Physics of ignition

Ignition occurs if the energy in the lightning channel, E_c, exceeds the energy required for ignition, E_{ig},

$$E_c > E_{ig} \tag{1}$$

The energy contained in a lightning channel is the time integral of the power, p, for the duration of the lightning stroke, or

$$E_c = \int_0^t p\, dt = \int_0^t i\, v\, dt \tag{2}$$

where i is the current, v is the voltage drop across the length of the arc through the fuel, and t is the duration of the stroke. Note that the current and the voltage are time dependent, requiring an integration over time.

As current runs through a fuel, it must heat the fuel to its ignition temperature to initiate combustion. This energy of ignition can be expressed as

$$E_{ig} = \varepsilon \rho V Q_T \quad (3)$$

where ε is an efficiency factor, approximately 1 for fine fuels (Frandsen 1973), ρ is the fuel bulk density, V is the volume of the lightning channel's path through the fuel (Fuquay *et al.* 1979), and Q_T is the energy per unit mass of fuel ignition (Wilson 1990). The last term takes the form

$$Q_T = Q_f + M Q_M \quad (4)$$

where M is the moisture content, measured as a fraction of the oven-dried mass. The heat of pyrolysis per unit mass of the fuel, Q_f, is defined as

$$Q_f = \int_{T_{amb}}^{400°C} (dQ/dT)\, dT \quad (5)$$

Susott (1982b) provides values for Q_f for various fuels.

The parameter Q_M is the heat of vaporization per unit mass of any water in the fuel (Wilson 1990). This is defined as

$$Q_M = \int_{T_{amb}}^{100°C} c_{p_w} dT + l_v \approx 4.18(100 - T_{amb} + 540) \quad [kJ/kg] \quad (6)$$

In equations (5) and (6), T_{amb} is the ambient temperature, 100°C is the boiling point of water, and 400°C is the temperature at which pyrolyzation, or the production of flammable gas, is essentially complete.

The described ignition process is still speculation. Latham (pers. com.) has found that the lightning channel ignites an annualar region and actually destroys the fuel in the core of the discharge. Heating, and therefore ignition, is due to convection rather that radiation.

Lightning

Lightning is an atmospheric phenomena that occurs when charge buildup in cumulus clouds is sufficient to cause electrical breakdown in the atmosphere. Charge is then exchanged within the cloud (intra-cloud) or between the charged region in the cloud and the ground (cloud-to-ground).

Lightning flashes can be of negative or positive polarity depending on the sign of the charge exchanged. The polarity of lightning flashes depends on the source region of the lightning flash. Negative flashes come from the negative charge region in the center of the cloud, while positive flashes originate from the positive charge region found in the upper portions of the cloud. Coming from higher altitudes, positive cloud-to-ground flashes occur less frequent than negative cloud-to-ground flashes, and show different characteristics significant to fire ignitions.

The cloud-to-ground lightning flash (or ground flash) typically consists of four distinct stages: the stepped leader, the return stroke, the dart leader(s), and the subsequent return stroke(s). The first stage is the stepped leader, a small packet of charge that moves down towards the ground in small steps. As it approaches the ground, opposite charge accumulates on and above the surface, sending streamers up towards the approaching stepped leader. Upon attachment, a powerful return stroke is triggered, neutralizing charge deposited by the leader following the path of ionized gas left behind the leader. At this stage, the lightning flash may end or, if sufficient charge is generated, a dart leader is lowered to the surface, which, upon contact with the ground, triggers a subsequent return stroke. There can be several return strokes in a single lightning flash. Negative ground flashes typically contain three or four return strokes, while positive ground flashes almost always have only one return stroke.

The return stroke is the cause of lightning fires. Peak currents in a return stroke are in the order of tens of kiloamps and can heat wood to explosive temperatures. Yet, it is the current duration and not the strength that determines the likelihood of ignition.

The current in a return stroke is characterized by a rapid increase followed by an exponential decay. Some return stroke currents contain a phenomena called long continuing current (LCC). The long continuing current is a current of about 100 amps that last for forty milliseconds or more. Low currents within the wood for this length of time will heat the fuel gradually to ignition (Fuquay *et al.* 1967; Fuquay *et al.* 1972). Approximately 20 percent of negative ground flashes and 80 percent of positive ground flashes exhibit continuing currents of 40 milliseconds or more (Uman 1987), but these values are only estimates based on a few observations of a phenomena that may vary greatly with location and other physical conditions.

Some characteristics of negative and positive cloud-to-ground flash are summarized in table 1 (Uman 1987). For a comprehensive background on lightning, the reader is referred to textbooks by Chalmers (1967), Uman (1969; 1987), and Golde (1977).

Table 1. Characteristics of positive and negative cloud-to-ground flashes.

Characteristic	Negative	Positive
% occurrence	90	10
Average peak current (kA)	30	35
Average current half life (μsec)	30	230
Average number of strokes	3-4	1
% containing long continuing current	20	80

Fuel Conditions
Even when lightning strikes, the probability of ignition depends on fuel conditions. These include fuel type and fuel moisture.

In 1964, Taylor documented a study of over 1,000 Douglas-fir trees in Montana with lightning scars, revealing important interactions of lightning and the tree it strikes. First, lightning rarely hit the tip of the tree but, on average, struck at about 10 feet below the tip. When lightning strikes a tree, it follows a spiral path down along the grain of the outer layers of the wood towards the ground. About half the scars studied extended to the ground, while the other half terminated within six feet of the ground indicating that the lightning left the tree to make contact with the ground.

The fuel type in which ignition occurs is not always obvious. In many cases, the fire is ignited in the duff layers at the base of the tree and not in the tree itself. Barrows summarized the ignition points for 11,835 fires in the Rocky Mountains (Barrows 1951). Of the materials first ignited, 34% were dead snags, 30% was the duff layer, and 11% was wood on the ground. These numbers are supported by Kourtz (1967), who noted that, in a study of 3,615 lightning-fire reports from across Canada, 31% of fires were ignited in snags, and by Ogilvie (1989), who stated that of the 11 lightning-caused fire sites he inspected, 10 of the fires propagated through the duff layer.

Precipitation
The principal factor controlling moisture content is precipitation. The same convective conditions that lead to lightning also lead to convective rain showers. These showers can increase the moisture content of the fuels reducing their ignitability.

The effects of precipitation can be divided into three categories: amount, rate, and duration. Fosberg (1972) developed an equation for the moisture content of dead cylindrical fuels over time

$$\frac{\delta M}{\Delta M} = 1 - \zeta e^{-\lambda t} \qquad (7)$$

where δM is the actual change in moisture content, ΔM is the potential change, λ^{-1} is the response time, and t is time. The parameter ζ is the similarity coefficient, which is dependent on $\lambda^{-1}t$.

Through this equation, Fosberg found that duration was more important than amount or rate in determining the moisture content of dead, cylindrical fuel types. In essence, fuels can absorb only so much water while in contact before the water filters down through the soil. This can be applied to the fine fuel litter on the forest floor, which is highly susceptible to ignition.

Another aspect that must be considered, especially in the ignition phase, is the question of sheltering. Sheltering is a term used to describe the effect the tree canopy has on the amount of precipitation that reaches the ground. As the density of the forest canopy increases, the amount of precipitation that is intercepted by the canopy increases, reducing the impact precipitation has on the forest floor. The importance of this was shown by Chrosciewicz (1989). He showed that the fine fuel and duff moisture contents of samples taken in stand openings and under stand canopy and were highly different with predicted values significantly drier than the stand openings.

Survival

The survival phase is the time between the ignition of a fuel and the time in which flaming combustion begins. Between these two times, the lightning-caused ignition remains smouldering in the fuel, possibly for several days, until either it dies out or, under the right weather conditions, it bursts out into active flaming combustion.

Researchers in Missoula have been studying the characteristics of smouldering fires, such as survival, rates of spread, and heat evolved. Using excelsior, Wilson (1985) derived an extinction index

$$n_x = \frac{\ln(S\ h_v/Q_M)}{(Q_f/Q_M+M)} \qquad (8)$$

where S is the fuel surface area per unit horizontal area in the fuel bed, h_v is the gaseous heat of combustion (Susott 1982a), and M is the moisture content. The numerator represents the fraction of heat released from the flaming zone that is collected by the fuel, while the denominator is the energy required to sustain combustion. Wilson tested the n_x parameter for 417 test fires. Using logistic regression, he found strong correlations between n_x and the probability of marginal burning and between n_x and the probability of "steady state" fires with contiguous flame front.

Arrival

The final stage of a lightning-cause fire occurrence is the arrival stage. The arrival phase is the stage at which a smouldering fire translates into full combustion on the surface. Once a fire reaches this stage, it becomes governed by the three fire behavior components: weather, fuel, and terrain.

The parameter most likely to change a fire from smouldering to flaming combustion would be the weather. While in the duff, the smouldering fire is relatively unaffected by the changing weather conditions, but when it reaches the surface, a small wind gust may be all that is required to trigger flaming combustion in dry fine fuels.

Wind, temperature, and relative humidity are principle factors in determining the fine fuel moisture. Temperature and relative humidity go through a diurnal cycle that affect fine fuel moisture. These effects are also felt in the duff but the diurnal trend is dampened. Wind has a drying affect on the fine fuel moisture and also is a controlling factor in the intensity and the spread rate of surface fires. The right combination of wind and fine fuel moisture will determine the time of arrival.

THE FUQUAY MODEL

Models to predict lightning caused fire ignitions are few. To date, the only model that has been used operationally is one first developed by the researchers at the Intermountain branch of the US Forest Service.

In the seventies, as part of the *Project Skyfire*, Fuquay *et al.* developed a model of the lightning ignition environment (1979). This model has been generally accepted and has been applied (with variations) by some agencies to predict lightning-caused fire occurrences (Latham 1983; Kourtz and Todd 1992).

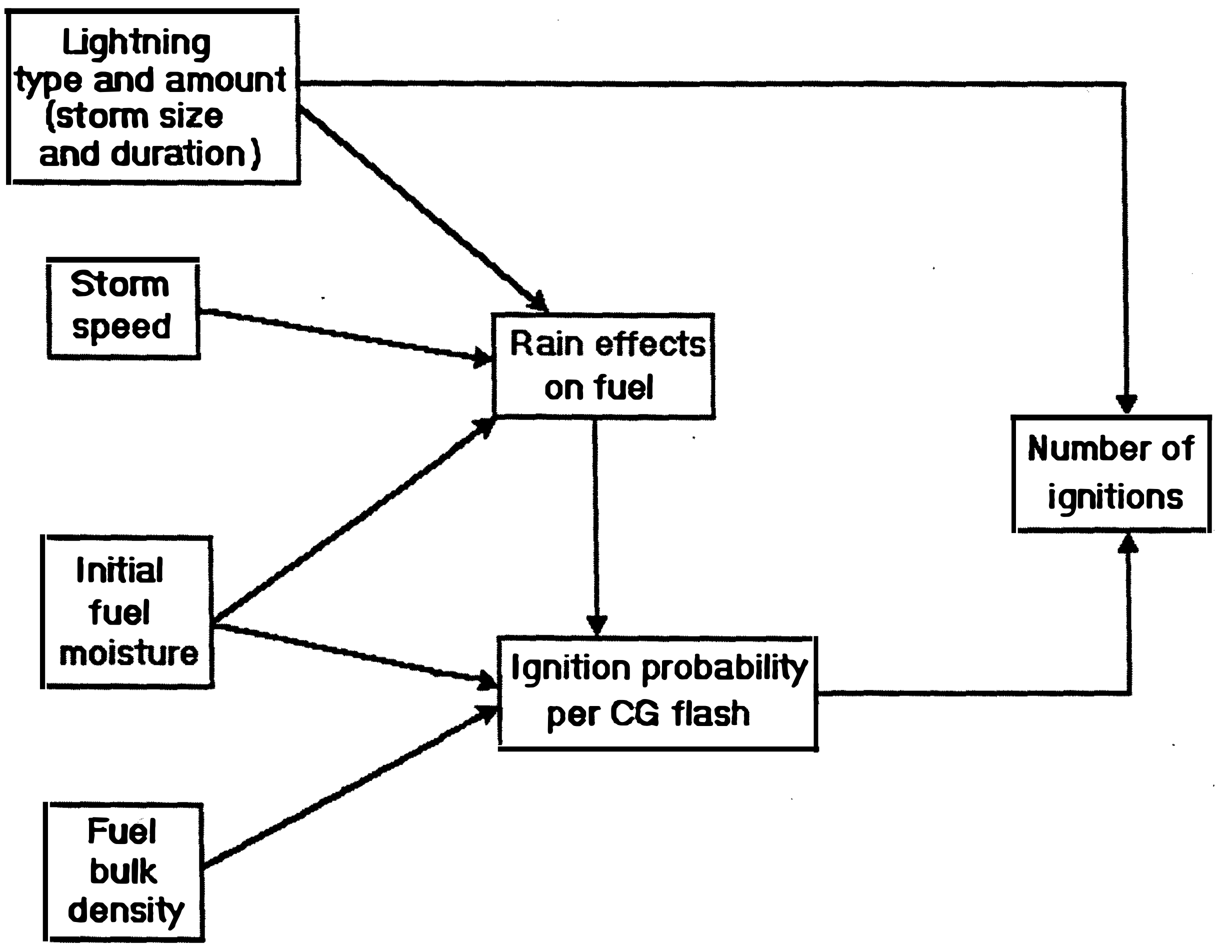

Figure 1. Fuquay's model of the lightning ignition fire environment (adapted from Fuquay *et al.* 1979).

Figure 1 is a flow chart illustrating the conceptual structure of the interactions involved in Fuquay's model. Input required by the model include the *lightning type and amount (storm size* *and duration), storm speed, initial fuel moisture,* and *fuel bulk density.* Intermediate values include the *rain effects on fuel* and the *ignition probability per CG flash.* The model predicts *number of ignitions* for an area.

Inputs

Lightning type and amount is the type and number of ground flashes over a given area. Type includes the polarity of flashes and whether flashes terminate in or out of the rain area. This information is estimated by the lightning activity level (LAL), an index ranging from 1 to 5 (LAL 6 is a special case) to estimate the actual number of ground flashes over a given area. The LAL index is a product of another report by Fuquay (1980), and is based upon radar echo heights, convective weather observations, and precipitation reports.

The *storm speed* determines the areal extent of precipitation. This is assumed to equal the 500 mb winds.

The *initial fuel moisture* can be determined through standard fire weather calculations such as the Canadian Forest Fire Weather Index (FWI) system (Van Wagner 1987) or, in the US, the National Fire Danger Rating System (NFDRS) (Deeming *et al.* 1972).

The *fuel bulk density* values developed for the NFDRS are tabulated in Fuquay's report. Forest fuel types included are tundra, western annual grass, pine-grass, western long-needled conifer, short-needled conifer (normal dead), short-needled conifer (heavy dead), Alaskan black spruce, sagebrush-grass, and eastern pine (plantation).

Intermediate Values

Rain effects on fuel is estimated from the lightning activity level and the storm speed. The LAL value provides an estimate of the duration of precipitation, which, following equation (7) determines the fine fuel moisture. Also, multiplying the duration by the storm speed gives the area covered by the storm.

Ignition probability per CG flash is evaluated through the relationship described by equation 1. Since only ground flashes with long continuing current components are assumed to cause ignitions, the number of probability of ignition per CG flash is the probability per LCC event multiplied by the fraction of LCC events per CG events. In Fuquay's model, the proportion of ground flashes with long continuing currents is a fixed percentage of the number of ground flashes: 20% of negative ground flashes and all positive ground flashes.

Output

Fuquay's model predicts the *number of ignitions* expected over the given area. This would represent the maximum number of fires to be expected from a single storm. As the model does not address the issues of survival or arrival, it fails to describe when ignitions become reported fires.

PROGRESS

When Fuquay designed his model, certain assumptions had to be made because of data availability. Since then, developments in both research and technology have filled a number of these gaps.

Ignition

Lightning detection
Originally, the lightning type and amount was determined using Fuquay's lightning activity level (LAL) index (Fuquay 1980). Since Fuquay first developed the model, lightning detection systems have come into use. These systems can detect individual cloud-to-ground lightning flashes within a detection network with great accuracy (Figure 2), and provide information on the polarity, the multiplicity (number of return strokes), and signal strength. The signal strength, a measure of the peak magnetic radiation field of the first return stroke, has been found to be proportional to the peak current, (Orville 1991), which may be useful to ignition prediction.

The wide band magnetic gate detection system (Krider *et al.* 1976; 1980) produced by Lightning Location and Protection (LLP) of Tucson, Arizona is in wide use in Canada. The LLP system can detect 70% of lightning ground flashes within 350 km of a direction finder (Mach *et al.* 1986). The accuracy of ground flash locations are 2 to 5 km (Nimchuk 1990).

A second system is the Lightning Position And Tracking System (LPATS) (Bent and Lyons 1984). The LPATS system is a short baseline time-of-arrival technique that determines the distance of a ground flash from an array of detectors based upon the difference in arrival times between detectors of the arrival of the magnetic signatures of lightning ground flashes (Uman 1987). Less documented than the LLP system, LPATS claims it can detect long continuing currents, although this author could not find papers to substantiate this.

Lightning occurrence prediction models
In recent years, efforts have been put into producing models to predict both lightning occurrence and frequency (Andersson 1989; Anderson and Charlton 1990; Reap 1990; Anderson 1991). The model most applicable to lightning-caused fire occurrence prediction is the one by Anderson (1991).

Anderson's model is a scheme to forecast lightning over Alberta. This was accomplished through the development of lightning occurrence and lightning frequency prediction models. These models were built using statistical modelling and map analysis, using LLP and upper air soundings as the data. Figure 3 illustrates a spatial interpolation of the model's predictions of lightning occurrence probability.

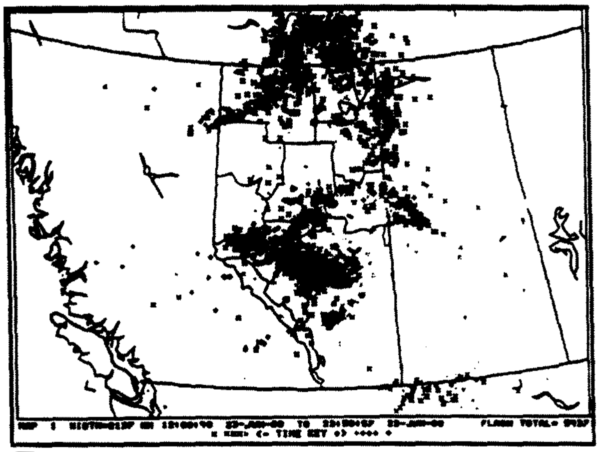

Figure 2. Lightning detection map for June 23, 1988.

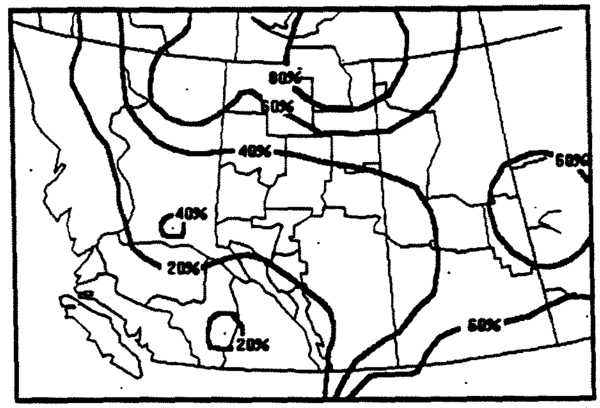

Figure 3. 0000 UTC June 24, 1988 negative lightning occurrence prediction map.

Long continuing currents

Shindo and Uman (1989) studied 90 negative cloud-to-ground lightning flashes in Florida looking for return strokes exhibiting continuing current characteristics. They found 22 long (greater than 40 msec), and 11 short (between 10 and 40 msec) continuing currents.

Two points in this paper stand out as being important to fire occurrence prediction. First, multiplicity is very important in determining the likelihood of continuing currents. Very few flashes (1 out of 19) with single strokes contained continuous currents. Multiplicity is a standard output of lightning detection systems and, thus, may be a good indicator of ignition. Also, the initial peak electric fields, and hence the peak currents, in return strokes with continuing currents were lower than return strokes without. This would suggest that peak current, which can be estimated from the detection system output, may not be a useful indicator of ignition. Average amplitudes of continuing currents in the study were primarily between 30 and 200 amps.

Ignition probabilities

Using a lightning-simulator, Latham and Schlieter studied the ignition probabilities of a number of fuels including duff, live wood, and punky wood under different moisture contents (Latham and Schlieter 1989). They found that moisture content was the most significant predictor of ignition and that depth of fuel was important in certain duff fuels. Equations were built for the probability of ignitions in each fuel type using stepwise logistic regression.

Studying lightning-caused fires in Northwestern Ontario, Flannigan and Wotton (1990) found that the Duff Moisture Code (DMC) and the multiplicity were the most significant predictors of daily lightning-caused fire occurrences. Their linear stepwise regressions were able to describe nearly 50% of the variance. They also found a DMC threshold value of about 10 (equivalent to a moisture content of about 240%) for ignitions. It is interesting to note that they found that positive ground flashes have a poor correlation with ignitions, contrary to common belief. It must be noted that Flannigan and Wotton's work concentrated on ignitions and did not address the problem of holdover (smouldering) fires.

Survival

Smouldering fires

As in the probability of ignition, the probability of a smouldering fire surviving depends on fuel and moisture content. Using the Canadian Forest Fire Weather Index (FWI) System, Kourtz *et al.* (1974) found a survival threshold at a Duff Moisture Code (DMC) of 20 (equivalent to a moisture content of about 200%). Kourtz took this further by developing the Smouldering Index (SMI) defined as

$$SMI = DC\ e^{\frac{-300}{DMC^2}} \tag{9}$$

where DC is the Drought Code of the FWI system. Index values below 75 indicate little chance of smouldering, while values above 100 indicate a good likelihood that a fire will continue to smoulder.

Frandsen (1987) and Hartford (1990) used a logistic regression approach similar to Wilson (1985) in their studies of other fuels. Frandsen determined that moisture content and mineral content were important factors for the survivability of smouldering fires in peat-moss and Douglas-fir duff. Hartford supported this conclusion and introduced organic bulk density as an important parameter.

Arrival

Fire behavior

The point when a fire arrives depends on fire behavior conditions, primarily the rate of spread. The Initial Spread Index (ISI) is a standard component of the FWI system. Combining fine fuel moisture with wind speed, the ISI is an index of fire spread rate. Tithecott (1991) built logistic regression models to predict the number of arrivals. He found that ISI and DMC were the best predictors of arrival for the 1990 fire season in Ontario.

Several models have been built to model actual fire behavior (Rothermel 1972; Wilson 1990; Forestry Canada Fire Danger Group 1992). These models are driven by fuel classifications, indices of fire weather conditions, and terrain effects. Outputs from these models include rate of spread, fire intensity, fuel consumption, and the likelihood of crowning. A serious deficiency of these models for use in studying fire arrival is that most models were designed to predict fire behavior under moderate to high burning conditions. Estimates of marginal fire behavior have not been the focus and therefore have a weak link to fire occurrence research.

Fire extinction

Wilson's research on fire extinction (1985) may provide better insight into the problem. His extinction index, n_x, is ideally suited for fire occurrence prediction, but his work has limitations. Although his fuels were conditioned beforehand, he did not include external effects such as wind and slope. This was beyond the scope of his work and is not a criticism of his approach.

DISCUSSION

Significant progress has been made towards a firm understanding of the lightning-caused fire ignition environment, yet applying this knowledge into an operational lightning-caused fire occurrence prediction model is a difficult problem. Essential information required by the ignition models is simply not available. For example, ignition probability equations have been built for several fuels including various duffs and punky woods; yet, how is one expected to determine which fuel type a lightning flash hits when the location errors of detection systems are 3 to 10 kilometres? Other areas of major deficiencies include forest inventory, precipitation, and lightning current characteristics. Without this information, developers of lightning-caused fire occurrence prediction models must make do with educated guesses to overcome these inadequacies.

LIST OF SYMBOLS

c_{Pw}	specific heat of dry air at constant pressure
E_c	energy in the lightning channel
E_{ig}	energy of ignition of the fuel
h_v	gaseous heat of combustion
i	current
l_v	latent heat of vaporization
M	moisture content within fuel measured as a fraction of the oven-dried mass of fuel
n_x	extinction index
p	power
Q	heat per unit mass of fuel
Q_f	heat of pyrolysis per unit mass of fuel
Q_M	heat of vaporization of water in the fuel per unit mass of fuel
Q_T	heat of ignition per unit mass of fuel
S	surface area per unit horizontal area in the fuel bed
t	time
T	temperature
v	voltage
V	volume
ε	efficiency factor
ζ	similarity coefficient
λ	the inverse of the response time
ρ	fuel bulk density

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DIURNAL CYCLES OF TEMPERATURE AND RELATIVE HUMIDITY IN ALBERTA [1]

BY

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AND

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1992

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DIURNAL CYCLES OF TEMPERATURE AND RELATIVE HUMIDITY IN ALBERTA

INTRODUCTION

Latitude is a strong determinant of weather and climate. For example, the inverse relationship of mean monthly or annual temperature and latitude is well documented. Topographical features also significantly influence weather and climate. The combination of latitudinal and topographical influences have produced two major fire climate zones in Alberta. These zones are generally defined by the mountains and foothills of the Rocky Mountains, and the boreal forests of northern and central Alberta.

The objective of this study is to develop mean monthly diurnal temperature and relative humidity cycles for the two fire climate zones of Alberta during the core fire season period from April to October.

Since fine fuel moisture content is strongly influenced by relative humidity, the diurnal temperature and relative humidity cycles largely determine the characteristics of the daily burning period. This study should help describe the seasonal variation of burning periods in the major fire climate zones of Alberta.

DATA COLLECTION

Hourly observations of temperature and relative humidity are available from a limited number of stations in the forested areas of Alberta. The stations selected for the study were High Level, Edson and Pincher Creek airports. These locations should be representative of the northern boreal forests, the mid-latitudes of central Alberta and the southern east slopes forests, respectively. Although climatological means are normally calculated for a 30 year period, the study utilized a 20 year period from 1971 to 1990 as data for High Level were not available for the longer period.

RESULTS AND ANALYSIS

Mean Monthly Diurnal Temperature and Relative Humidity Cycles

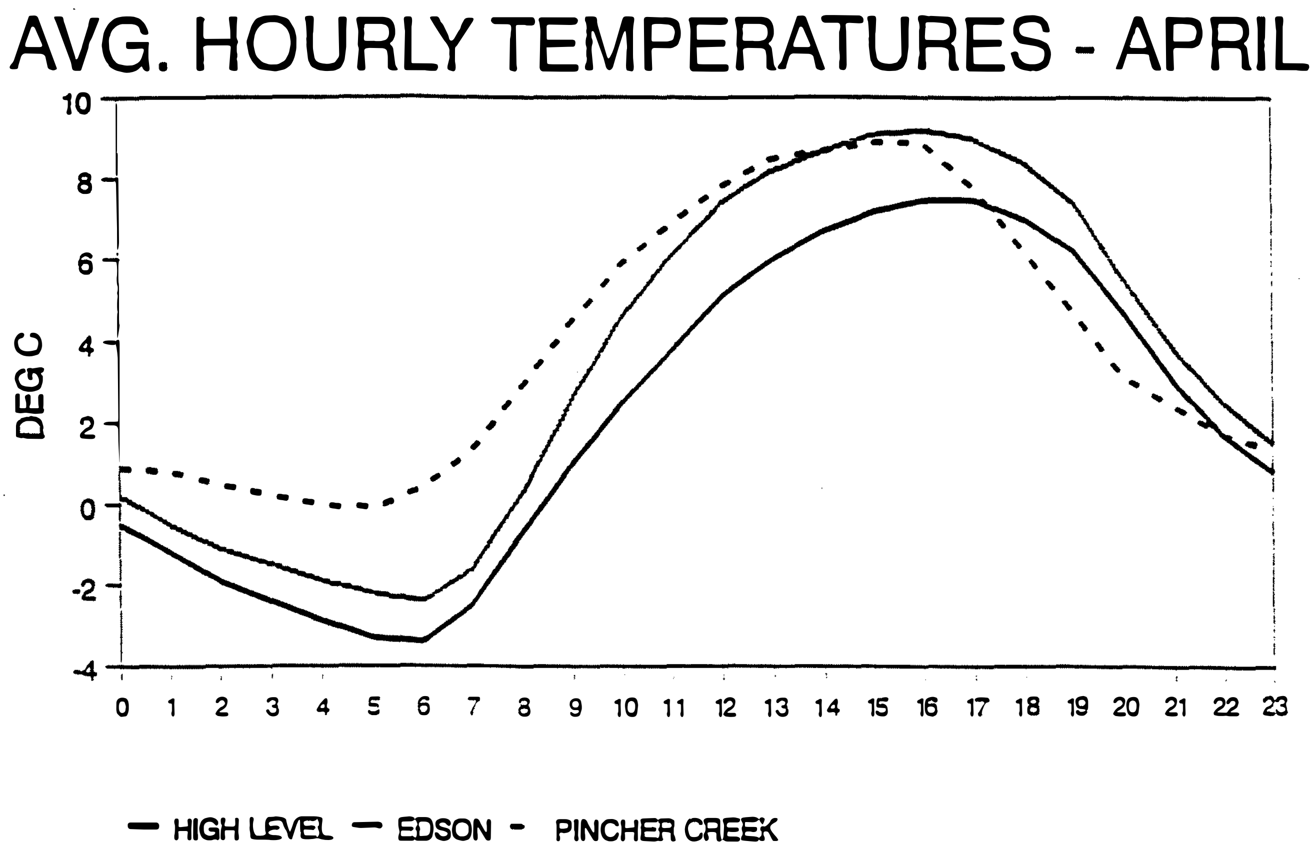
There are three characteristics of the daily temperature and relative humidity cycle which influence fire potential and behaviour:

1) The daily maximum and minimum values.
2) The difference between the daily maximum and minimum relative humidity values or the relative humidity recovery.
3) The time when maximum and minimum values are reached and the length of time between these values.

i) April - May

The fire history of the boreal forest has shown that spring is frequently a season of active fire business. The mean diurnal curves for April and May (Figs. 1 and 2) display characteristics that would increase ignition potential and enhance burning conditions in the boreal forest. Although High Level is the coolest location during April, it experiences the lowest humidities. The humidity values at High Level are the lowest throughout the diurnal cycle and display the poorest recovery. The minimum humidity value is reached later in the day than at Edson and Pincher Creek.

These low humidity values are the result of a lower atmospheric moisture content produced by modified arctic airmasses that frequently influence northern and central Alberta during April and a lack of evapotranspiration. Lakes and other surface moisture sources are generally frozen further limiting the moisture supply. By May the northern latitudes are receiving significantly more daylight and surface heating. Sources of surface moisture may remain limited for a substantial portion of the month. Consequently, High Level records the highest maximum temperature values as well as the lowest minimum



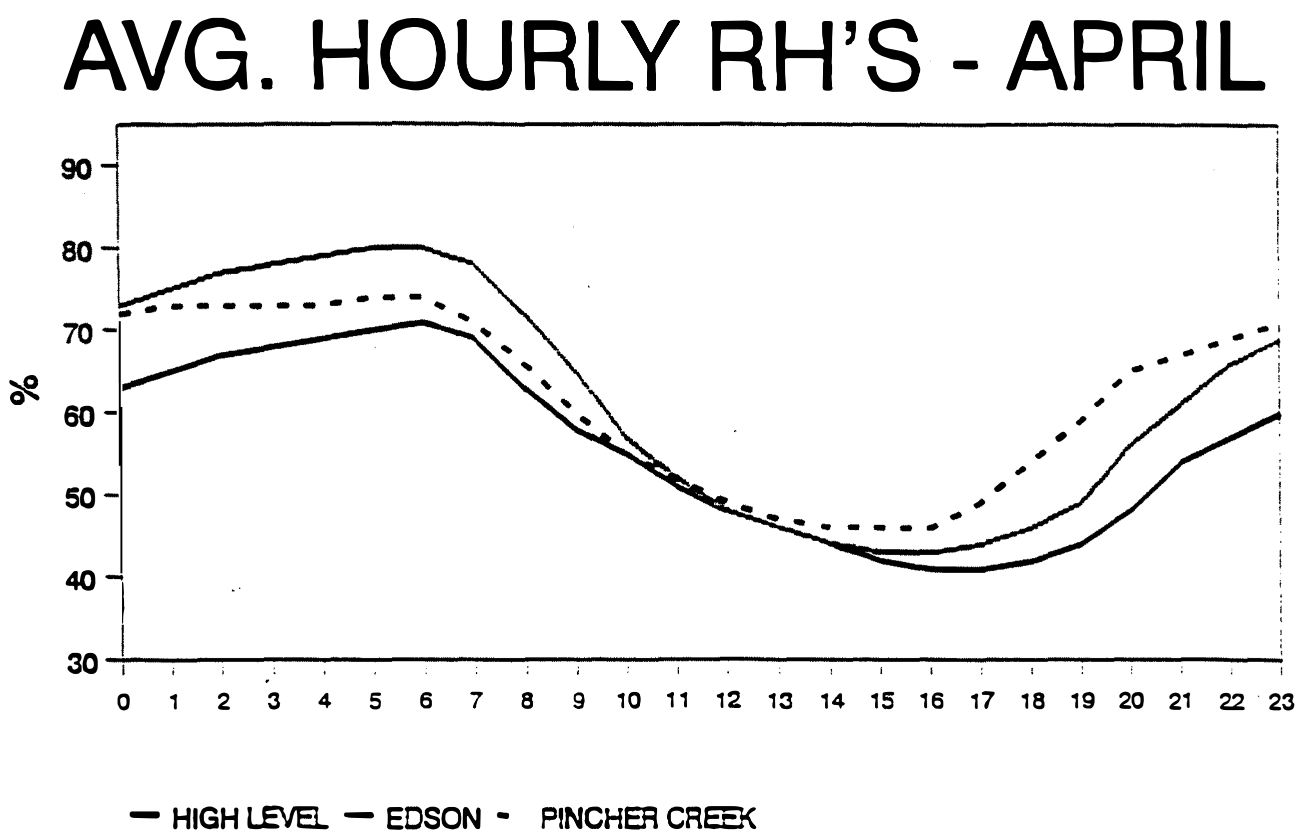
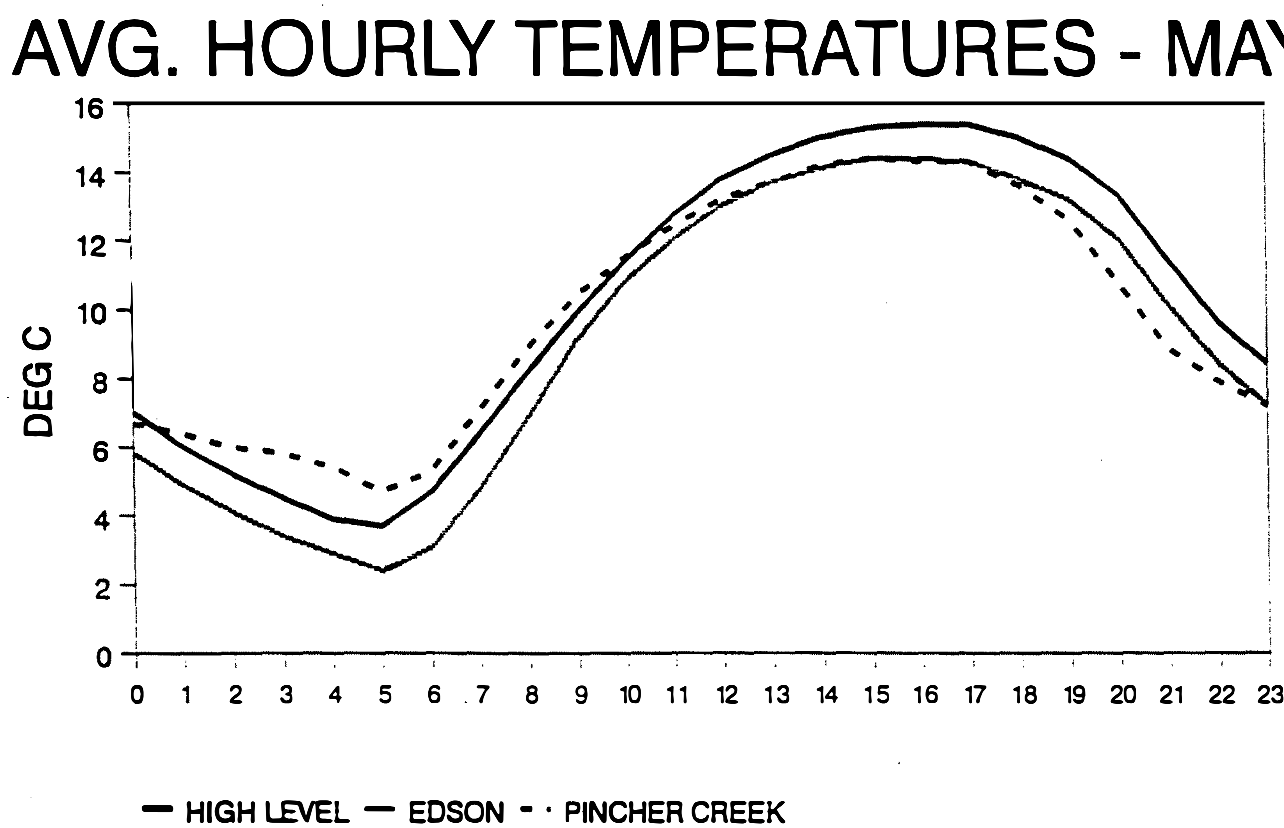


Figure 1 Average hourly temperature and relative humidity - April



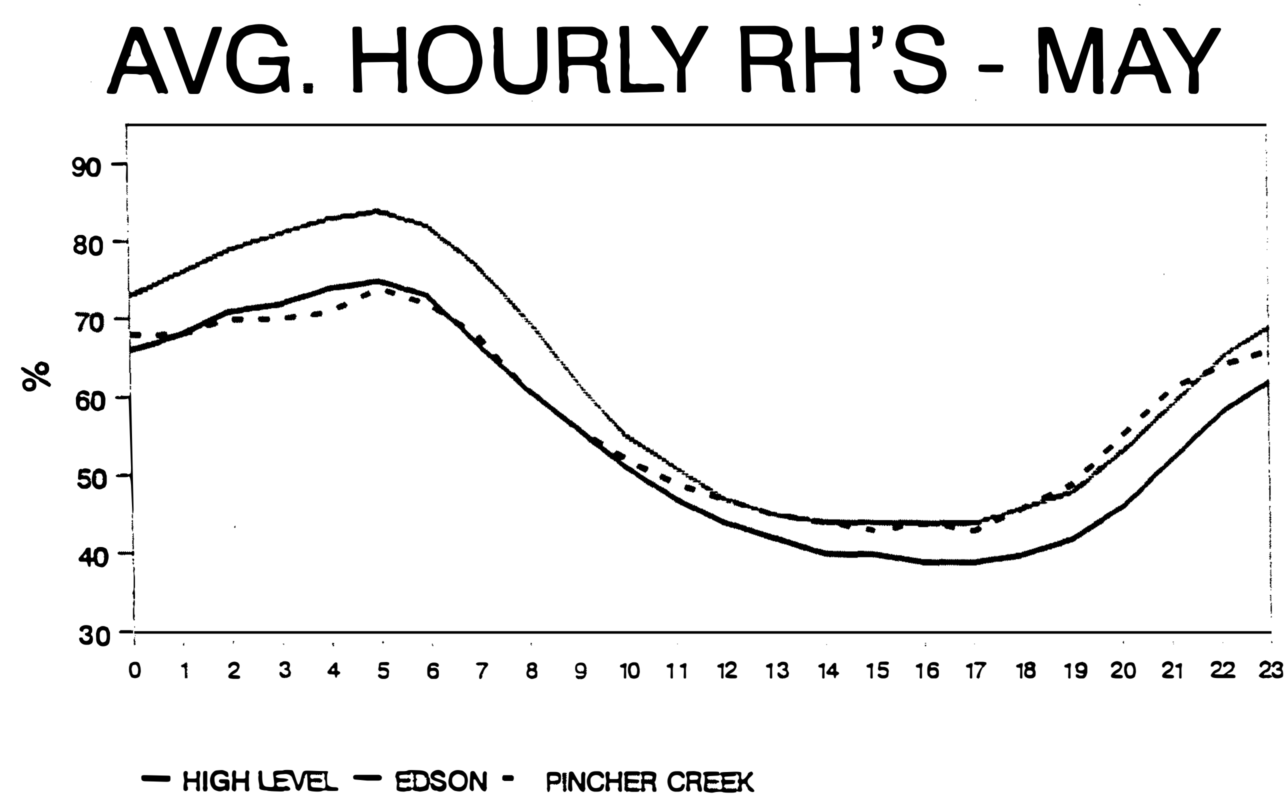


Figure 2 Average hourly temperature and relative humidity - May

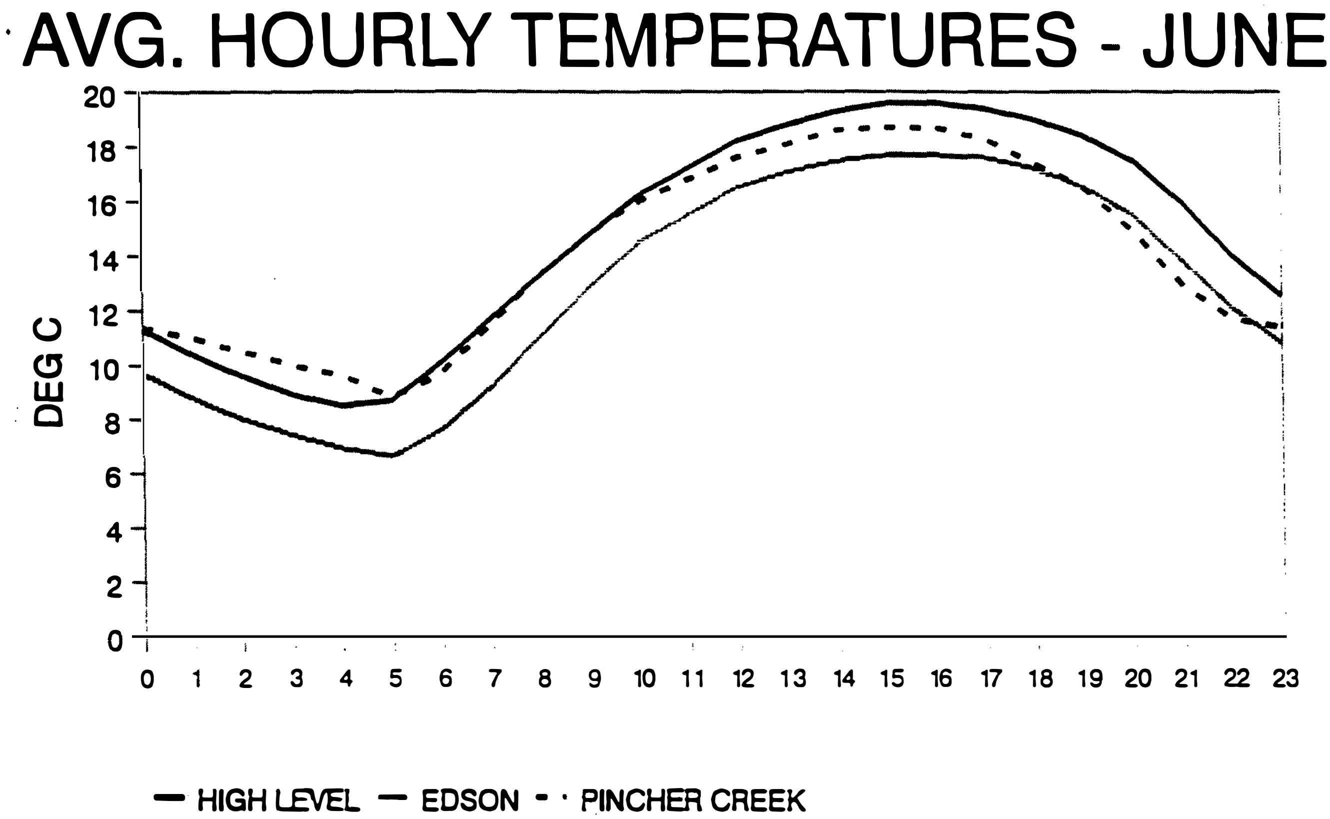
humidities.

The fire history of the east slopes in spring contrasts sharply with that of the boreal forest. April and May are typically characterized by a low level of fire activity. The southwestern mountains and foothills normally receive their greatest snowfall during April and May. The influence of spring precipitation and melting mountain snowpack is likely reflected in the higher maximum humidity values of the Edson and Pincher Creek diurnal cycles. During both months, Edson also displays the greatest humidity recovery.

ii) June, July and August

Significant changes occur in the diurnal cycles during the months of June and July (Figs. 3 and 4). Humidity values at High Level show a marked increase throughout the daily cycle in June and particularly July. The mean monthly minimum humidity rises from 38% in May to 43% in June and 50% in July. Increased evapotranspiration and the increase in temperature of boreal lakes account for much of this substantial increase in humidity values. These mean humidity conditions are not favourable for easy burning conditions. Potential fire problems arise when humidity values deviate significantly below the mean in conjunction with dry medium and heavy fuels.

While summer humidity values are trending higher in the boreal forest, the southern east slopes experience an overall decrease in humidity values. In July, Pincher Creek humidities are significantly lower than at High Level and Edson throughout the diurnal cycle. The humidity recovery at Pincher Creek is also the poorest; the humidity recovers to 73% from its mean daily minimum of 38%, while Edson and High Level recover into the 80 to 90% range from a minimum value of 50%.



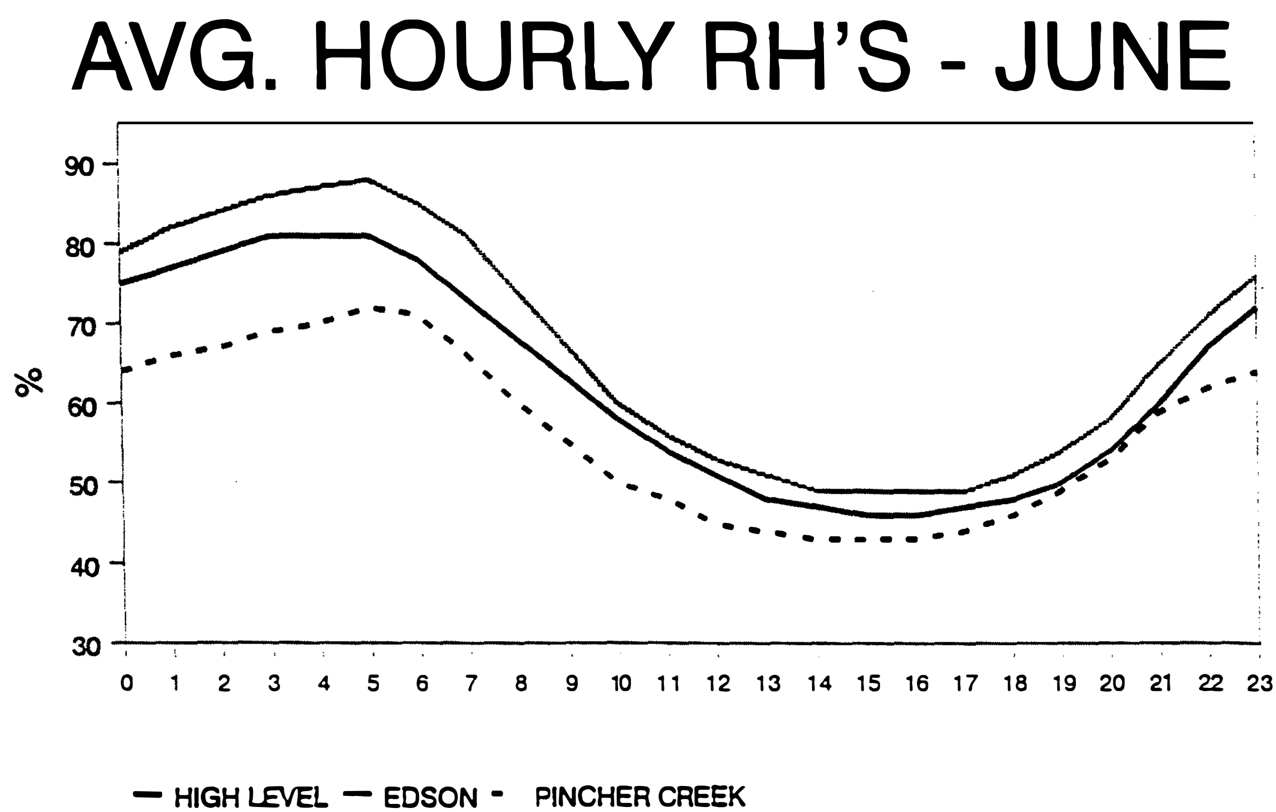
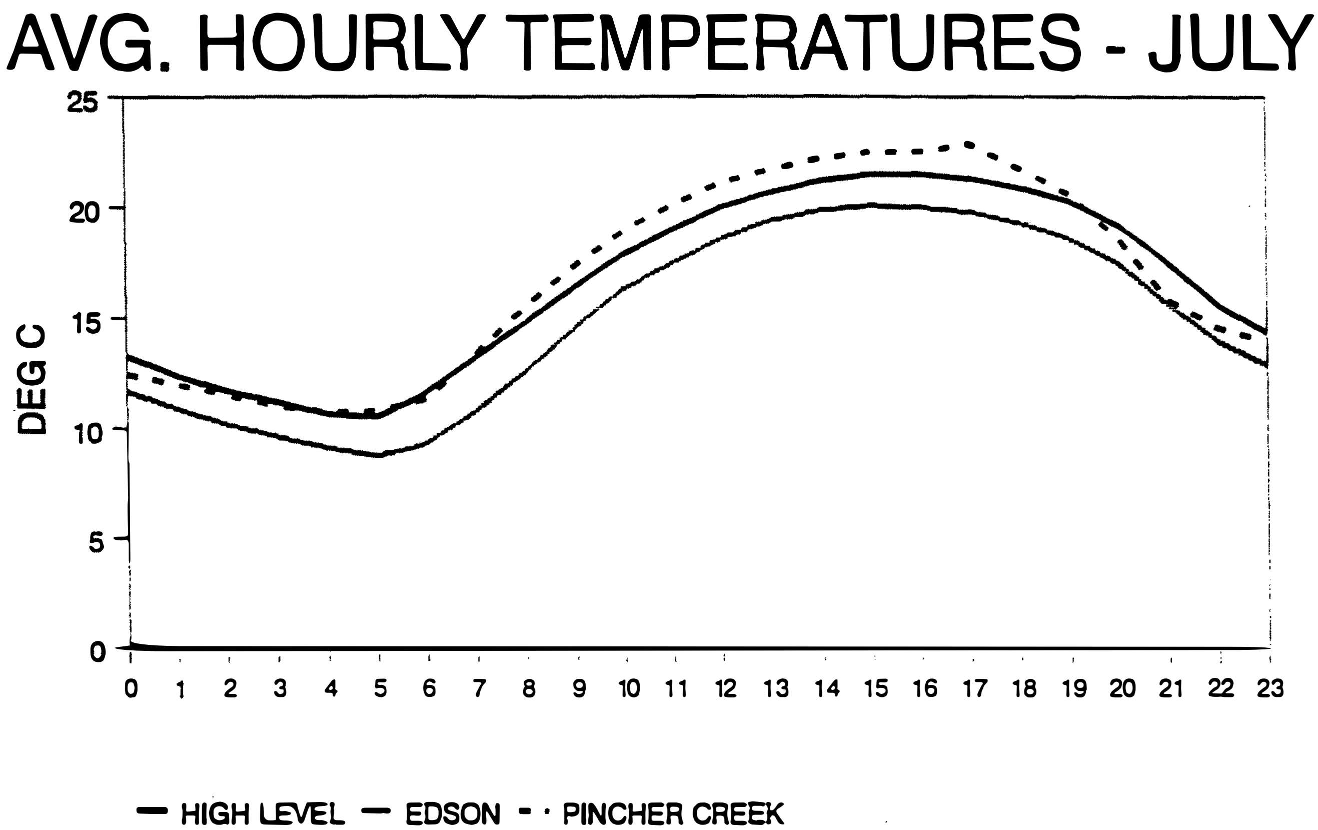


Figure 3 Average hourly temperature and relative humidity - June



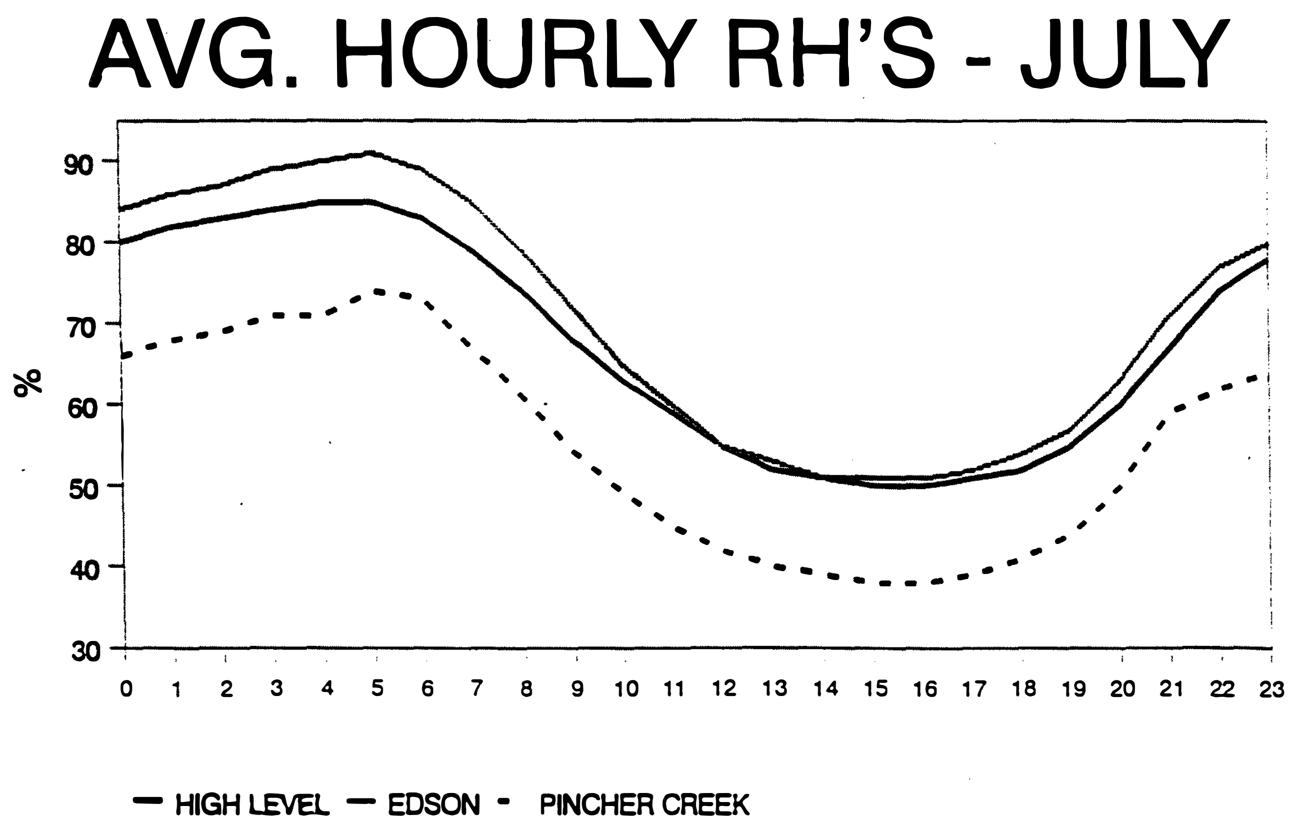


Figure 4 Average hourly temperature and relative humidity - July

The June and July data clearly illustrate the lengthening of the burning period during the mid-summer months. Humidity values at all three stations begin to decrease earlier in the day and remain at or near their minimums for longer periods.

The diurnal temperature cycles also undergo significant change during June and July. Latitude and elevation largely determines the temperature regime of a given site. During April, High Level is the ccolest station despite it being the lowest in elevation; latitude is clearly the most influential temperature determinant in early spring. However, in May and June, High Level is the warmest of the three sites. This suggests that elevation exerts a stronger influence during late spring as insolation increases. As summer progresses into July, all stations reach their peak temperature values with Pincher Creek recording the highest mean monthly maximum temperature. Terrain induced subsidence and a high probability of exposure to hot continental airmasses due to its most southern latitude, likely outweigh the influence of Pincher Creek's higher elevation. Pincher Creek also exhibits in all months a more rapid decrease in temperature during the late afternoon and evening; this characteristic is a result of the shadowing effect of the mountains.

In August the general characteristics of the diurnal cycles are similar to July, however, there are some important differences (Figure 5). Temperatures have decreased approximately two degrees throughout the cycle at all three stations as the fall season approaches. The shorter daylight period also results in a more rapid recovery in humidities late in the afternoon and a subsequently shorter burning period. Minimum humidity values have increased marginally at High Level and Edson while Pincher Creek experiences a more significant increase from 38% to 42%.

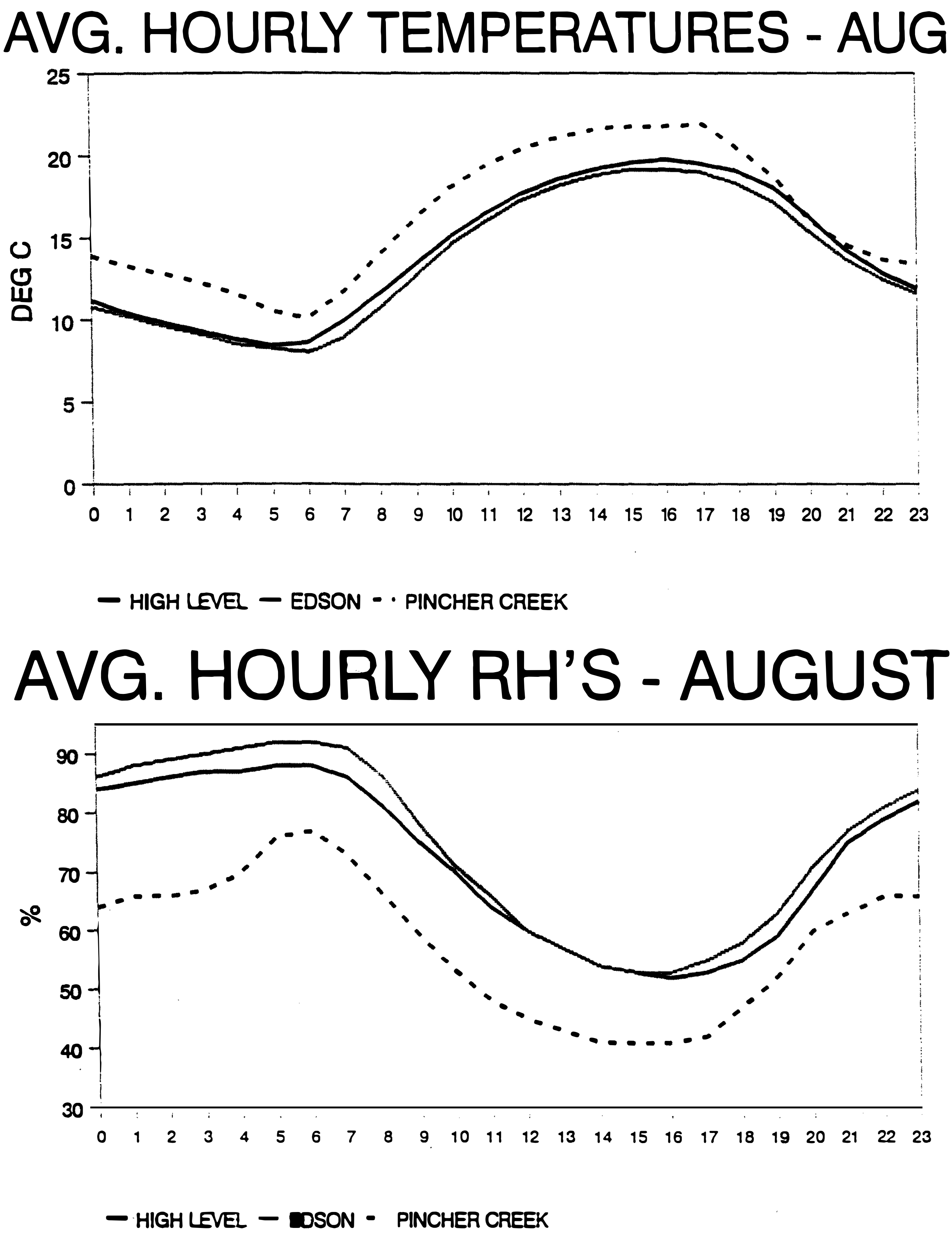
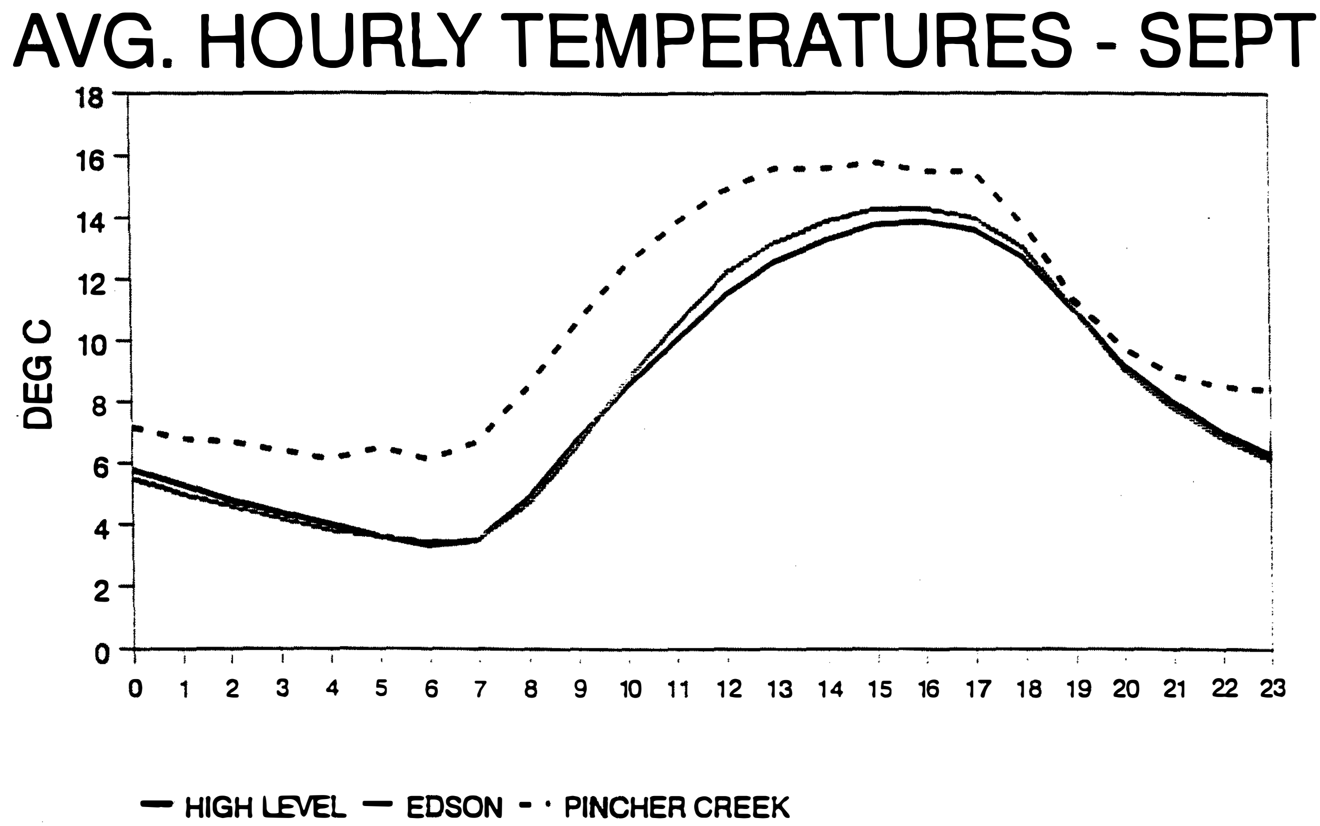


Figure 5 Average hourly temperature and relative humidity - August

iii) <u>September - October</u>

The onset of fall generally brings cooler and dry weather to Alberta. This seasonal change is clearly reflected in the diurnal cycles for September and October (Figs. 6 - 7). All stations have cooled by three to five degrees in September, however, little change has occurred in humidity cycles; reduction in evapotranspiration processes likely acts to counter balance the overall cooling experienced during September. The length of the burning period is further shortened as the number of daylight hours continues to decrease. High Level becomes the coolest location in September with the periodic return of arctic airmasses and snow to more southern latitudes. Pincher Creek maintains its position as the driest location during September.

Significant cooling is evident at all three stations in October. The greatest drop in mean maximum temperature occurs at High Level from near 14° C in September, to 5° C in October. The shorter daylight and terrain shadowing effects at Pincher Creek shift the time of maximum temperature to about 1400 hrs, the earliest of all locations. Additionally, the mean minimum temperatures at High Level and Edson fall below freezing. The mean minimum humidity value at High Level increases to 61% in October resulting in only a 20% difference from the maximum value and a very limited potential burning period. However, the humidity cycles for Pincher Creek, and Edson in particular, indicate the mean minimum humidities are lower in October than in September. Lack of evapotranspiration, lower precipitation, and stronger Chinook wind events generate these drier conditions. Fire history has shown late fall brings a higher risk of grassland fires to southern and central Alberta. Curing of these fine fuels has generally occurred by October; a heavy loading of cured grass during



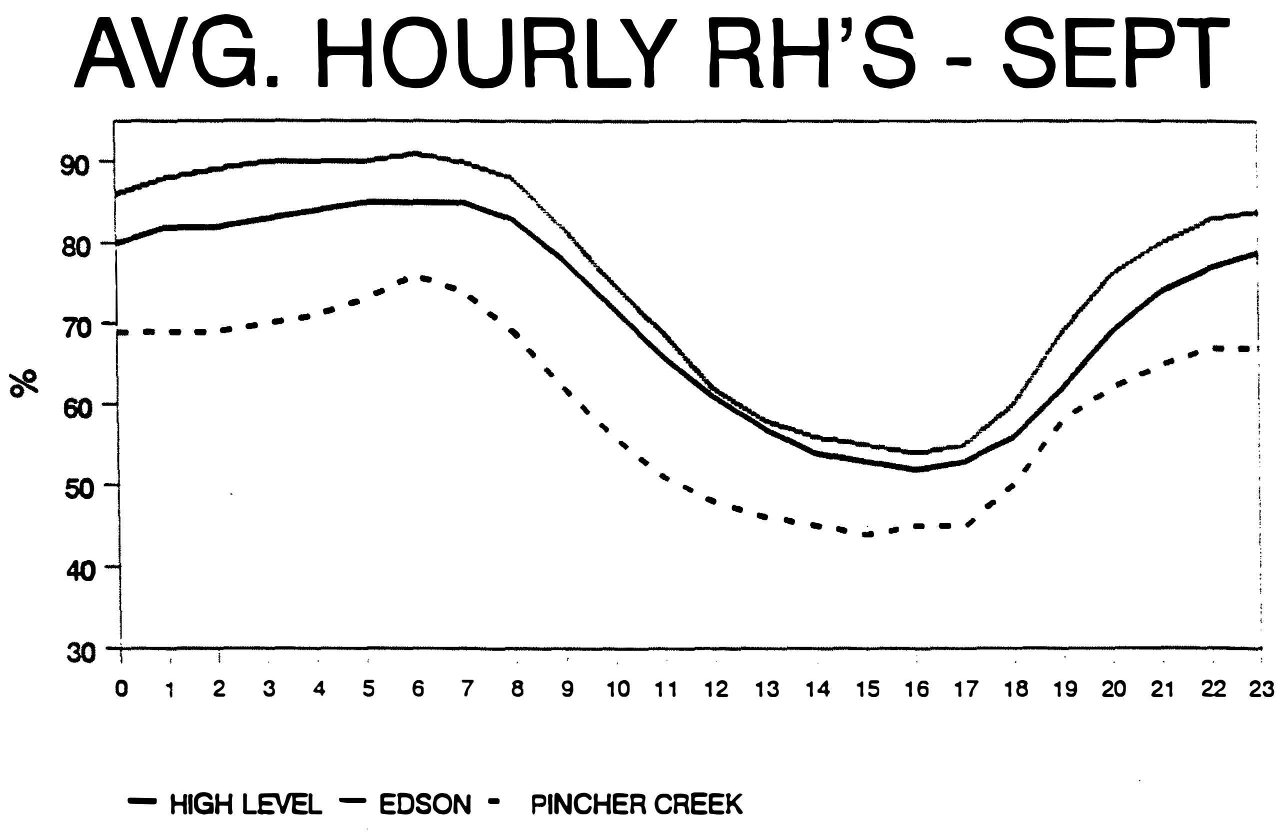
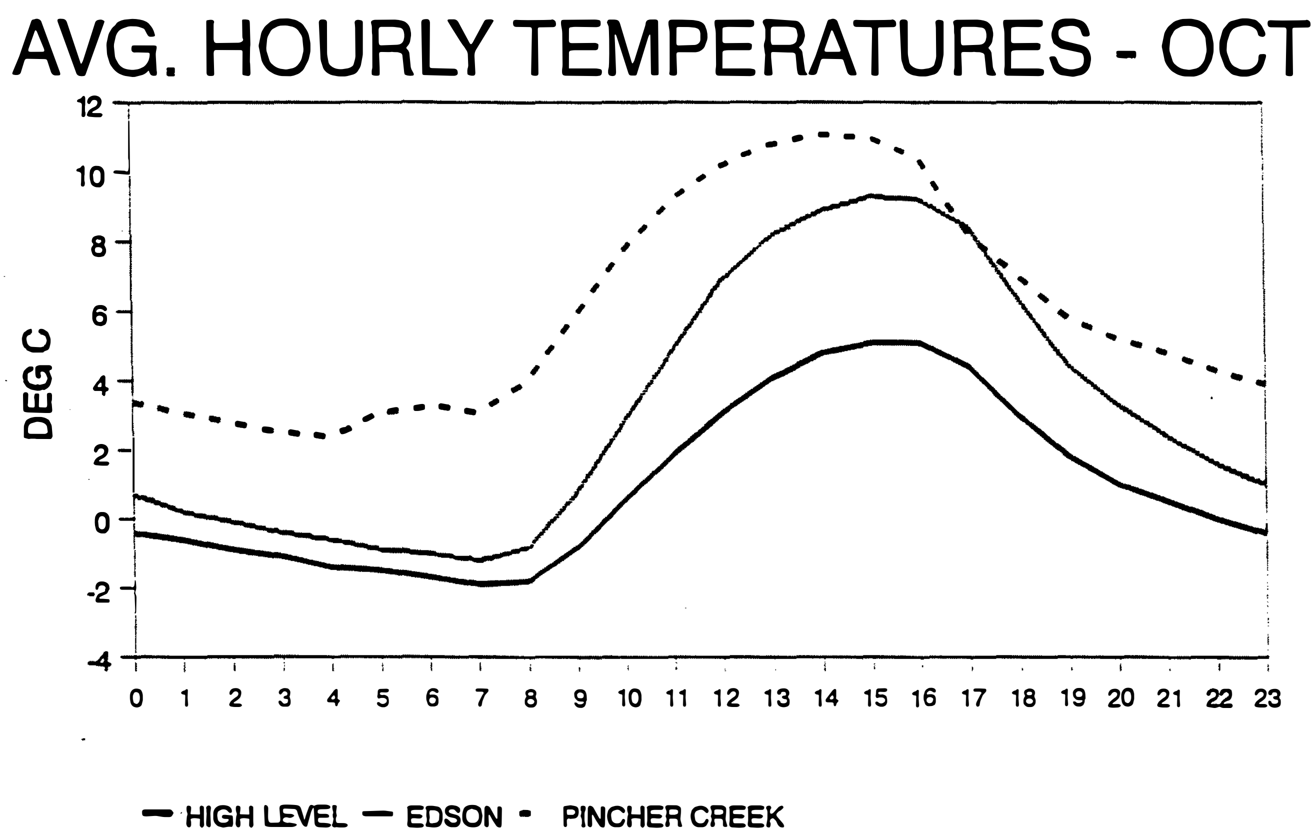


Figure 6 Average hourly temperature and relative humidity - September



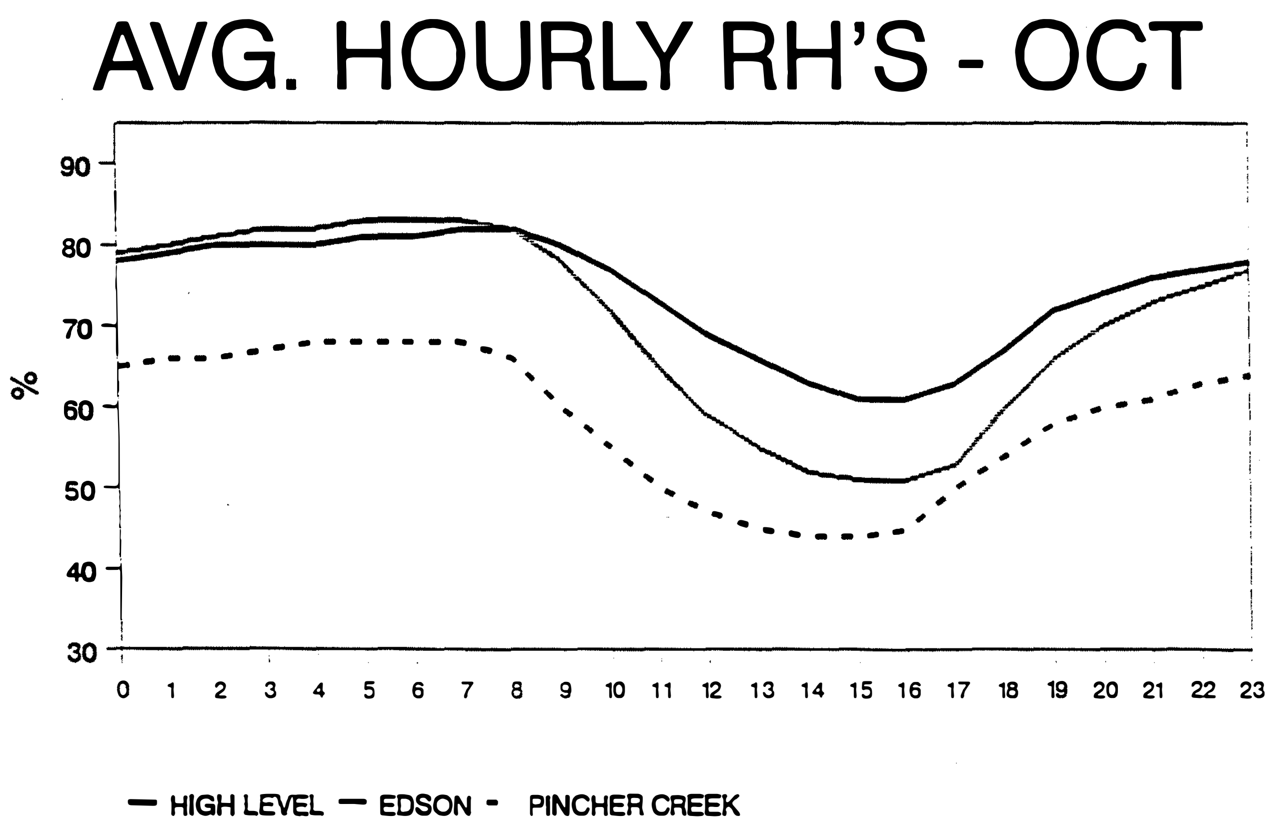


Figure 7 Average hourly temperature and relative humidity - October

this dry month, an ignition source, and a strong Chinook wind event lasting only a few hours, have produced several major grassland wildfires.

Humidity and Fire Danger

The fire weather environment depicted by the mean diurnal temperature and relative humidity cycles is not conducive to the occurrence of problem fires. Extreme fire behaviour and large wildfires are the product of extreme environmental conditions. An examination of the frequency of humidity conditions favourable for fire ignition and growth would provide a more detailed picture of the fire climate regions in Alberta.

The Fire Weather Index (FWI) components of the Canadian Forest Fire Danger Rating System are based on a daily weather observation taken at noon standard time. The Fine Fuel Moisture Code (FFMC) and Initial Spread Index (ISI) are indicators of ignition potential and rate of spread. The Duff Moisture Code (DMC) is an indicator of the moisture condition of medium weight or depth fuels. Relative humidity strongly influences these FWI components, particularly the FFMC. The humidity condition at local noon largely determines the assessment of fire danger conditions for the peak of the burning period. Fire danger indices characteristic of high ignition potential or active fire behaviour events generally require noon humidity values of less than 40%. Monthly frequency distributions of noon humidity values were determined for the three stations.

Frequency Distributions

i) April

The mean diurnal cycles for April showed noon humidity values at the three locations were similar. The noon humidity frequency distribution for April (Fig. 8) reveals several important characteristics not reflected in the mean values. Edson experiences the highest frequency of noon humidity values below 40% followed by Pincher Creek and High

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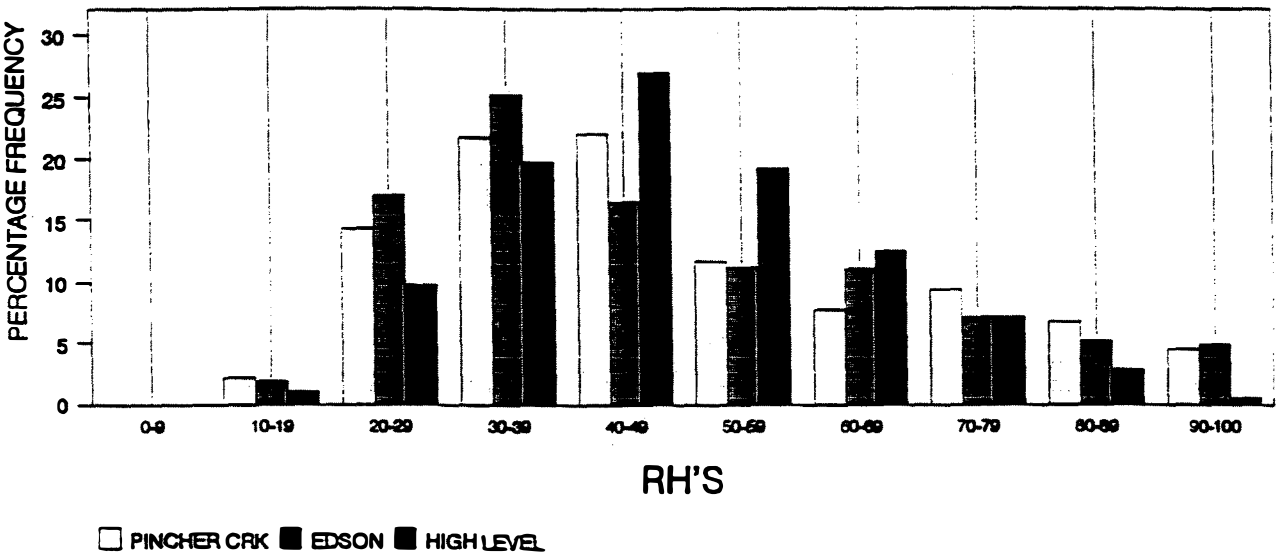

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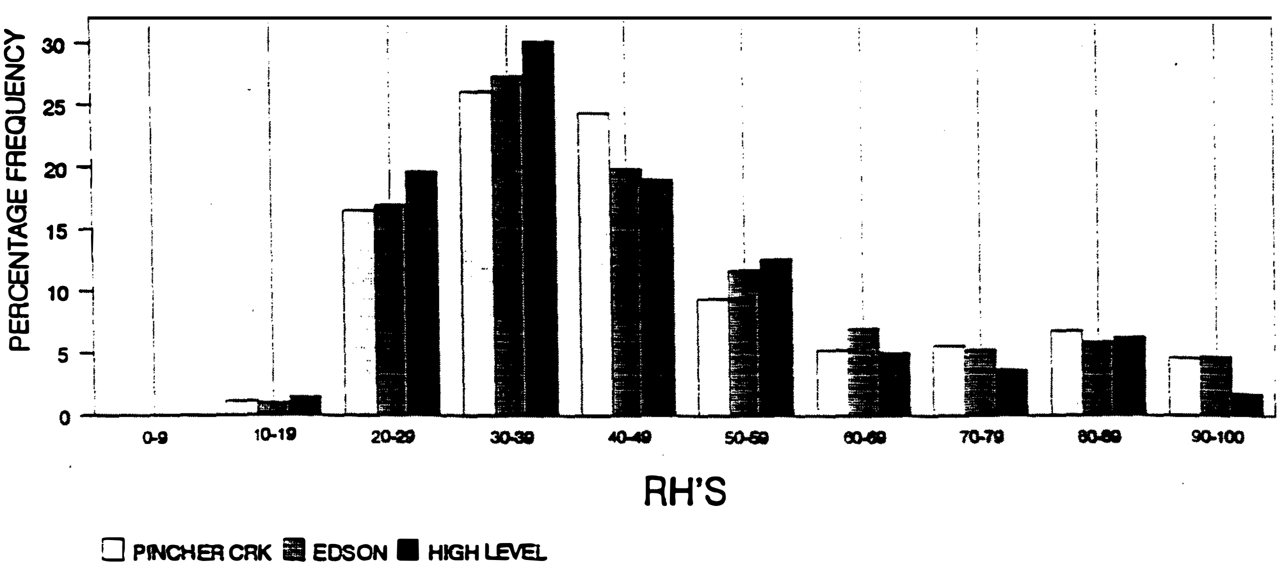


Figs. 8 (top) and 9 (bottom) Frequency of noon relative humidity values - April and May, resp.

Level. This characteristic would create a tendency toward higher FFMC values at Edson; although High Level displays a drier overall diurnal cycle with a poorer humidity recovery, the tendency would be toward lower FFMC values. The frequency distributions also show High Level has the lowest occurrence of noon humidities above 70%.

ii) May

This month sees an increase in the frequency of noon humidities below 40% at all three stations (Fig. 9). High Level displays the most significant change and records the highest incidence of humidities below 40% The incidence of extreme humidity values equal to or less than 20% is also the highest at High Level in May. The lengthening of the burning period and more frequent occurrence of low noon humidities at High Level, highlights the potential for active fire business frequently associated with spring in the boreal forest.

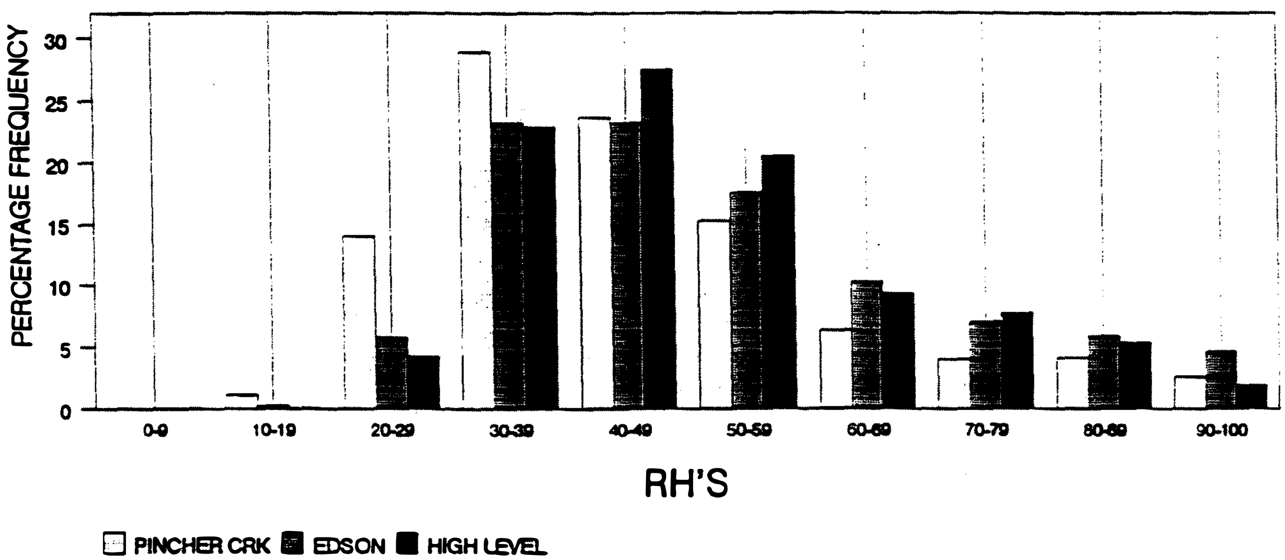
iii) June

The arrival of summer brings another major shift in the noon humidity frequency distributions (Fig. 10). High Level sees a return to more humid conditions as transpiration increases and surface moisture becomes available. This station records the lowest incidence of values below 40%; extreme values below 20% were not reached in June during the study period. Pincher Creek begins to emerge as the driest station with approximately 44% of noon humidity values below 40%.

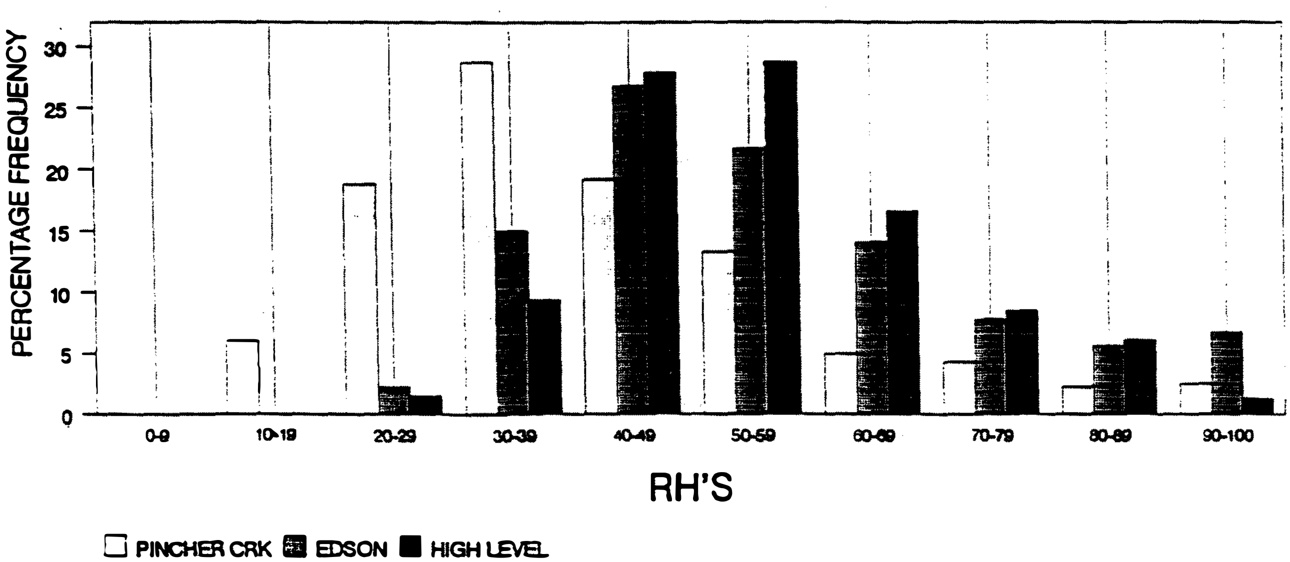
iv) July

The frequency of low noon humidity conditions continues to increase at Pincher Creek in July while Edson and High Level maintain a trend toward higher humidities (Fig 11). Approximately half of the noon humidities at Pincher Creek are below 40% during July. Additionally, it is the only

FREQUENCY DISTRIBUTION NOON RH VALUES --- JUNE



FREQUENCY DISTRIBUTION NOON RH VALUES --- JULY



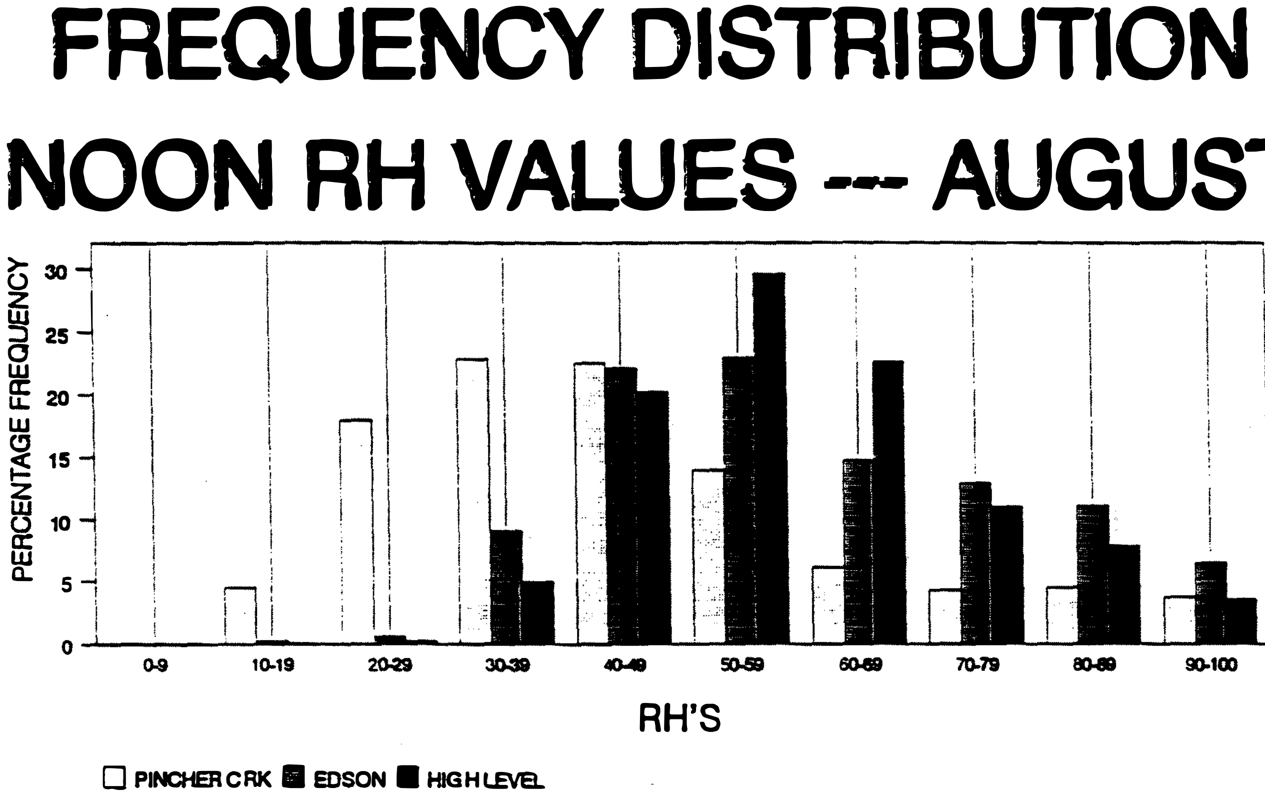
Figs. 10 (top) and 11 (bottom) Frequency of noon relative humidity values - June and July, resp.

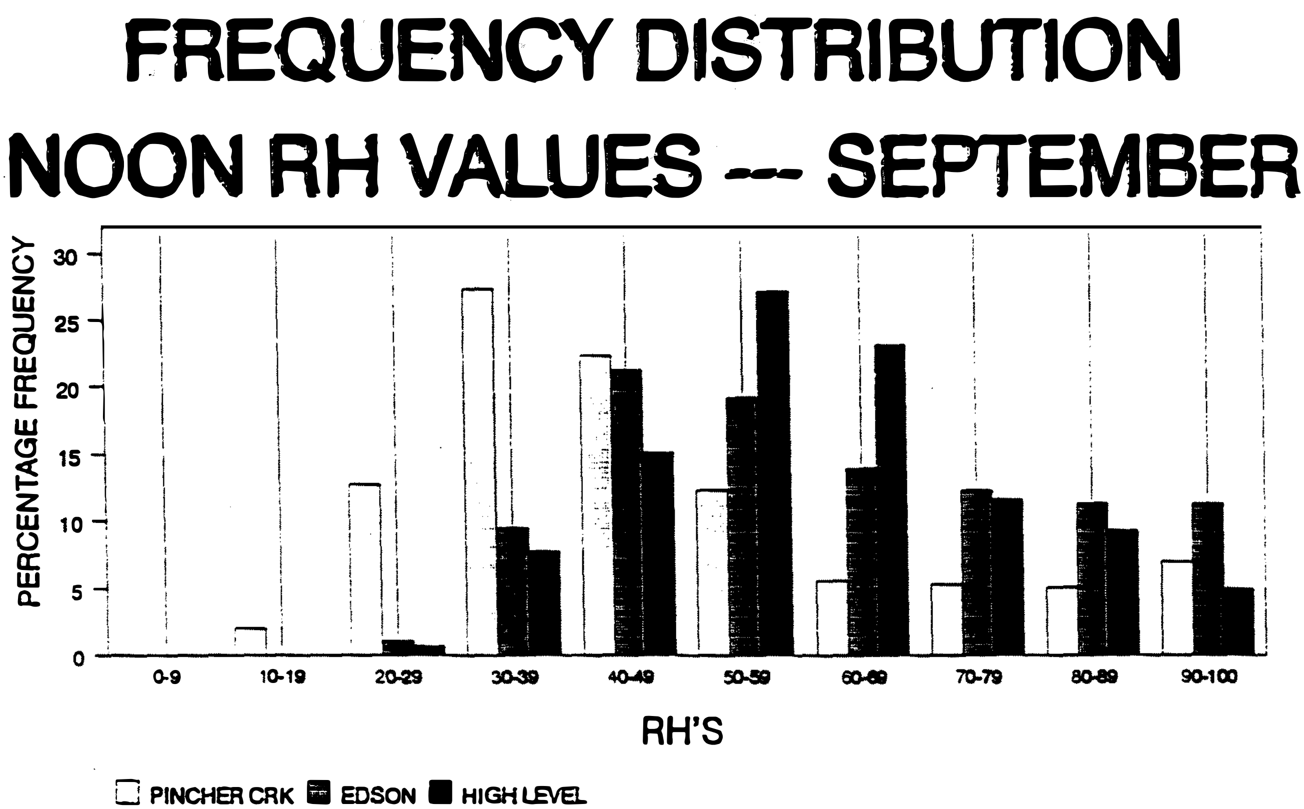
station to record noon humidity values below 20%; the frequency of these extreme values increases sharply from less than 2% in June to approximately 6% in July. The mode range, or most frequently occurring range of values, is 30 to 39% at Pincher Creek, 40 - 49% at Edson, and 50 - 59% at High Level. Over half of the noon humidity values at High Level fall into the 40 - 59% range.

These data indicate the potential for high FFMC values in the east slopes of the Rockies is substantially greater than in boreal forests during July. This month also marks the onset of the lightning season in Alberta. Fire history clearly indicates lightning is a more effective ignition agent in the boreal forests than in the east slopes despite the generally lower FFMC values of the boreal regions. Fuel type and topography explain this difference. The spruce-lichen woodland of the boreal forest provides the deeper duff fuels most conducive to lightning ignition. Higher cloud bases characteristic of thunderstorms in boreal regions have been shown to generate higher intensity lightning flashes and have a greater risk of being relatively dry. Thunderstorms in the east slopes are lower based, generally develop under high humidity conditions and frequently remain quasi-stationary during their life-cycle. Consequently these storms are frequently wet. Shallow duff fuels and a lack of fuels at higher elevations more prone to be affected by lightning activity also contribute to the low lightning fire incidence in the east slopes.

v) <u>August</u>

All three stations show a decrease in the frequency of humidity values below 40% in August (Fig. 12). The mode range at High Level remains between 50 - 59% but at a higher frequency than July. The number of values above 60% also shows a significant increase.





Figs. 12 (top) and 13 (bottom) Frequency of noon relative humidity values - August and September, resp.

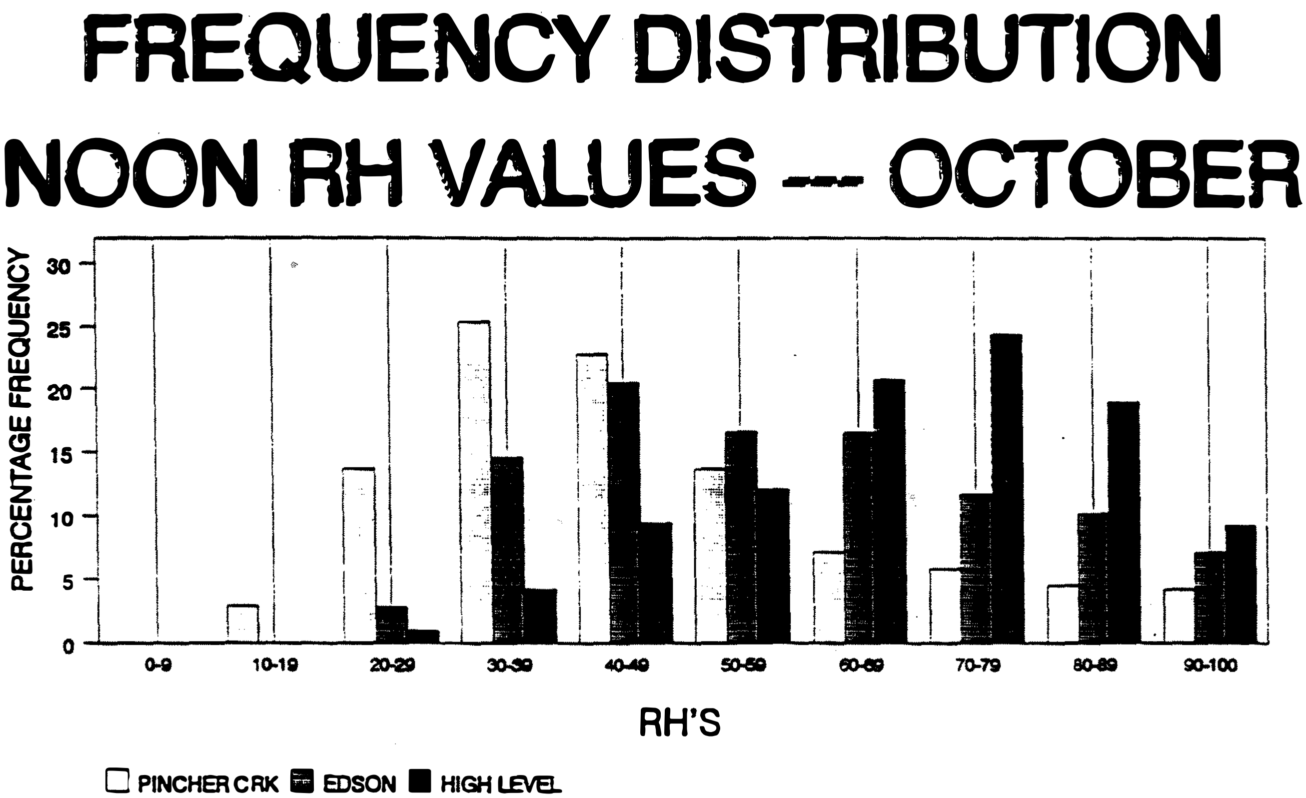


Figure 14 Frequency of relative humidity values - October

Pincher Creek records a drop in the frequency of humidity values below 40%, however, the number of extreme humidities below 20% shows little change. The mode range at Edson increases to the 50 - 59% range; this station also receives the highest frequency of noon humidities above 70%.

vi) September

The approach of fall brings a reduction in transpiration processes and a generally drier period, particularly in the boreal forests. Edson and High Level see a slight increase in the frequency of noon humidities below 40% (Fig. 13). The mode ranges remain unchanged at High Level and Pincher Creek but fall to 40 - 49% at Edson. The potential for grass fires often increases at this point in the fire season in the east slopes forests, particularly after wet summers.

vii) October

The persistant increase in noon humidity values at High Level continues in September (Fig. 14). The mode range increases to 70 - 79% during this markedly cooler month. Few fire problems have been experienced in the northern boreal forest during October. Pincher Creek sees its mode range remain at 30 - 39%, but also records a slightly higher frequency of extreme low noon humidities below 20%. Edson displays an increase in frequency in the 20 - 29% and 30 - 39% range as well. Normally low precipitation and topographic effects likely contribute to this late season increase in extreme humidity values. Grass and range fires are not uncommon in the southern east slopes and plains during October.

Frequency of Temperature/Humidity Crossover

A review of several problem wildfire situations in Canada and the U.S. found that rapid changes in fire behaviour were frequently associated with a numerical convergence of temperature and relative humidity values. Numerous cases of extreme fire behaviour were noted under conditions where the temperature exceeded the relative humidity value (e.g., 30^{o} C and 25%). This information led to a "rule of thumb" for Alberta fire managers and fire weather forecasters as a quick means of assessing the potential for ignition and extreme fire behaviour. The rule of thumb is that when the temperature is close to or exceeds the value of the relative humidity, watch out for fire problems. The "crossover" rule of thumb has been documented on many problem fires in Alberta.

The occurrence of conditions described by the crossover rule of thumb was tabulated for each of the study locations by determining the percentage of hourly observations in each month that satisfied the numerical criteria:
relative humidity - temperature $<=$ 5.

Temperature/relative humidity crossover events are clearly a spring fire season characteristic at High Level (Table 1). In May, 23.6% of the 1700 hr. readings satisfy the rule of thumb criteria; nearly a quarter of the days in May will record a crossover event in High Level. Another characteristic of these events is the majority occur between 1100 and 2000 hrs. In the absence of precipitation during the previous few days, the occurrence of crossover conditions at the fire weather observation time of local noon will generally produce FFMC values of approximately 92 or greater.

The frequency of crossover events and the possibility of extreme FFMC values diminishes throughout the summer and fall. The time window for these events also turns progressively shorter later in the fire season.

The Edson crossover data also displays the highest frequencies in May, however, the total number of events is significantly lower than at High Level (Table 2). Overall, Edson shows a low frequency and a weak seasonal variation of crossover events. The

Table 1 Hourly frequency (%) of temperature and relative humidity crossover conditions at High Level

TIME (LST)	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.2	0.0	0.0	0.0	0.0	0.0	0.0
3	0.2	0.0	0.0	0.0	0.0	0.0	0.0
4	0.2	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.2	0.8	0.0	0.0	0.0	0.0	0.0
11	0.8	3.1	0.6	0.2	0.2	0.0	0.0
12	1.9	7.4	2.2	1.3	0.3	0.0	0.0
13	3.2	11.8	4.8	2.9	1.0	0.7	0.0
14	3.7	16.6	8.5	4.8	2.4	0.7	0.0
15	4.9	21.1	10.2	6.6	3.9	1.0	0.0
16	6.5	22.2	13.0	7.6	5.2	1.3	0.3
17	6.9	23.6	12.0	7.9	4.4	1.5	0.7
18	6.5	20.2	10.0	5.8	3.2	0.3	0.0
19	4.9	14.9	5.9	3.7	1.8	0.2	0.0
20	1.6	6.0	1.8	0.6	0.5	0.0	0.0
21	0.0	0.2	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 2 Hourly frequency (%) of temperature and relative humidity crossover conditions at Edson

TIME (LST)	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.2	0.3	0.3	0.0	0.0	0.0	0.0
11	1.9	1.9	1.2	0.6	0.3	0.2	0.0
12	4.3	5.1	3.6	1.3	0.6	1.0	0.0
13	5.2	8.1	5.3	4.0	1.2	2.4	1.2
14	7.0	9.8	7.1	7.3	3.1	4.8	2.9
15	9.2	12.8	10.5	8.6	4.9	5.9	4.2
16	10.6	13.6	10.3	9.1	5.4	6.5	4.2
17	10.2	13.1	9.3	8.6	4.0	5.2	2.8
18	8.6	10.9	8.2	5.9	1.7	2.1	1.1
19	4.3	8.8	5.0	3.4	0.6	0.5	0.0
20	1.3	3.4	1.5	0.8	0.2	0.0	0.0
21	0.0	0.3	0.5	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 3 Hourly frequency (%) of temperature and relative humidity crossover conditions at Pincher Creek

TIME (LST)	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT
0	0.0	0.0	0.0	0.3	0.0	0.8	0.8
1	0.0	0.0	0.0	0.8	0.0	0.0	0.0
2	0.0	0.0	0.0	0.8	0.0	0.0	0.0
3	0.0	0.0	0.0	0.8	0.8	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.8
5	0.0	0.0	0.0	0.0	0.0	0.0	0.4
6	0.0	0.0	0.2	0.2	0.3	0.0	0.2
7	0.0	0.0	0.2	0.2	0.3	0.0	0.2
8	0.2	0.2	0.3	1.5	0.6	0.0	0.2
9	0.2	0.6	1.3	3.8	3.3	1.0	1.0
10	0.8	2.0	4.0	10.2	8.1	2.8	2.1
11	3.1	4.3	7.2	16.2	15.5	5.5	4.0
12	5.1	7.1	11.3	23.5	21.4	11.9	6.6
13	6.3	9.6	13.9	27.2	27.5	14.4	8.8
14	6.1	12.9	17.8	33.1	32.3	16.1	10.5
15	8.2	14.7	19.8	37.5	34.6	18.1	11.0
16	8.7	14.3	20.9	36.7	35.5	16.7	9.0
17	6.8	11.5	16.0	35.9	32.6	14.8	6.4
18	2.3	6.5	10.7	29.0	23.1	5.9	2.3
19	0.0	3.7	5.1	18.3	13.4	1.5	1.4
20	0.0	0.9	2.0	8.1	5.4	1.5	1.4
21	0.0	0.5	0.5	1.1	1.1	1.0	0.9
22	0.0	0.0	0.0	0.5	1.1	1.0	0.5
23	0.0	0.0	0.0	0.5	0.5	0.5	0.9

occurrence of extreme FFMC values at Edson would likely be most frequent in spring.

A substantially different crossover regime was found at Pincher Creek (Table 3). The seasonal variation in crossover events is significant with the peak occurrence recorded in July and only a slightly lesser frequency in August. During these months approximately 35 - 38% of all days will record a crossover event. The probability of extreme FFMC is also the highest of the three study locations.

Strong topographic effects are likely responsible for the large number of these crossover events. More significantly, the time window for crossovers at Pincher Creek is much wider than at the two boreal locations. Crossovers may occur at practically any hour at Pincher Creek. Several cases of nocturnal wildfires exhibiting extreme behaviour have been documented in the flashy fuel regions and plains east of the southern Rockies. Similar events have occurred under strong Chinooks during winter months with humidity values plunging to near 10%.

One of the more noteworthy cases of nocturnal wildfire in the east slopes occurred near Chain Lakes in February 1987. Chinook conditions produced temperatures of 14 to 15^{o} C and relative humidity values of 12 to 15%, for a five hour period between 2000 - 2300 hrs. Winds of 50 to 70 km/h drove a range and brush fire 10 km during this period killing several livestock. The glow of the fire was clearly visible in Calgary, situated 80 km to the north. Such events illustrate the variability of fire weather and fire danger conditions along the east slopes of southern Alberta.

SUMMARY

The use of averages in the description of fire climate help to identify the periods most likely to have fire problems. The data presented in this study provides a more quantitative basis for

- the reasonable perception held by Alberta fire managers that spring frequently brings a higher risk of fire problems to the boreal forests, while the east slopes experience most fire problems in the late summer and fall.

Alberta's fire history has shown that the majority of serious fire problems are associated with strong deviations from average humidity and fuel moisture conditions. The variable nature of Alberta's fire climate allows extreme conditions to develop beyond the boundaries of the typical or average fire season in the two fire climate regions of the province. This characteristic presents an ongoing challenge to fire managers.

THE DIAGNOSIS OF MOISTURE FLUX CONVERGENCE AS A CONVECTIVE FORECASTING TOOL [1 2]

90 - N - 97

by

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December 1990

ABSTRACT

Moisture Flux Convergence has been used extensively by the National Weather Service in the United States (Beckman, Nierow, Waldstreicher) for the past few years, and has been demonstrated to be a useful tool in forecasting convective weather. It seems that virtually every tephigram a forecaster sees during the summer shows enough instability that upon reaching the forecast temperature and dewpoint, thunderstorms will form. However, often not even a single cumulus cloud forms in what seems to be an extremely unstable airmass. Clearly there is some process in action that is preventing convection in these cases. The diagnosis of surface moisture flux convergence may give a clue as to why convection is localized.

RÉSUMÉ

Le National Weather Service des États-Unis utilise considérablement la convergence d'humidité depuis quelques années. Cette méthode s'est prouvée utile pour la prévision de temps convectif. En été, nous observons presque chaque jour une instabilité atmosphérique suffisante pour produire des orages pourvue que la température et le point de rosée prévus soient atteints. Mais, souvent il ne se développe aucun cumulus dans une masse d'air qui est apparemment très instable. Évidemment dans ces cas, il y existe un processus qui empêche le développement de nuages convectifs. L'analyse de la convergence d'humidité à la surface pourrait peut-être aider à expliquer le développement convectif localisé.

[1]A paper presented at the Sixth Western Region Fire Weather Committee Scientific and Technical Seminar, March 23, 1992, Edmonton, Alberta.

[2]Reprinted with permission of the Atmospheric Environment Service, Western Region.

[3]Meteorologist, Alberta Weather Centre, Atmospheric Environment Service.

1. INTRODUCTION

When convergence takes place at the surface, several things may happen.

1) First, as a consequence of continuity, there must be upward vertical motion in the boundary layer. This, in many cases, produces enough forced lift to initiate convection in an unstable airmass. It can also lead to the realization of potential instability.

2) Moisture suspended in the air will also converge, leading to an increase in the mixing ratio, which in turn results in more buoyancy of a convective parcel because of greater latent heat release. It may be argued that, because of the continuity mentioned earlier, the moisture will be forced upward and the mixing ratio will not increase significantly. This is partly true. The usual result in this case is a deeper moist layer. Once the boundary layer undergoes convective mixing, the end result will still be a higher moisture content in the resulting convective updraft. In the case of a strong low level inversion, this moisture will not be able to rise through the inversion. This leads to a rapid increase in surface dewpoints, and the formation of the "loaded gun" atmosphere.

3) If a capping inversion is present in the boundary layer, the vertical motion brought about by surface convergence may be enough to weaken this inversion and allow free convection to take place. Most tephigrams in the summer clearly show a low level nocturnal capping inversion.

2. THEORY

Mathematically, Moisture Flux Convergence (MFC) is the convergence of the product of the wind and moisture fields.

$$MFC = -\nabla\cdot(q\vec{V}) = -q\nabla\cdot\vec{V} - \vec{V}\cdot\nabla q$$

where $\vec{V}$ is the surface wind

$$= -q\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right) - u\frac{\partial q}{\partial x} - v\frac{\partial q}{\partial y}$$

and q is the mixing ratio

When broken down into coordinate form, two terms emerge, a mass convergence term and an advection term. The advection term is easy to "eyeball" when looking at a surface analysis. If the dewpoints upstream are higher, positive moisture advection is taking place. In most cases, however, it is the mass convergence term that contributes most to instantaneous increases in moisture. In other words, convergence will do more to change the moisture field in the short term than advection. This explains why moisture axes seem to maintain themselves in troughs, even when drier air is being advected into them.

In order to diagnose moisture flux convergence, an analysis must be done on three fields; the u and v components of surface wind, and the mixing ratio. This diagnosis has been in place on the Alberta Weather Center PC on a real time basis since late June 1990. The program links up to the HP1000, loads and decodes the SAs from in and around Alberta, performs the three analyses, and displays the derived field of moisture convergence. The program is written in Turbo BASIC, and takes about 9 minutes to run. Once translated to C on the HP9000, the program will require about 7 seconds, a little closer to 'real time'. At present, the analysis works on a 50 km grid spacing in order to accommodate some of the more densely clustered data points in southern Alberta. In 1991 Alberta Forest Service data will be included, requiring the grid spacing to be reduced to 25 km. This will increase the run time to about 60 seconds, but will only be necessary twice a day, as forestry data is available only twice a day.

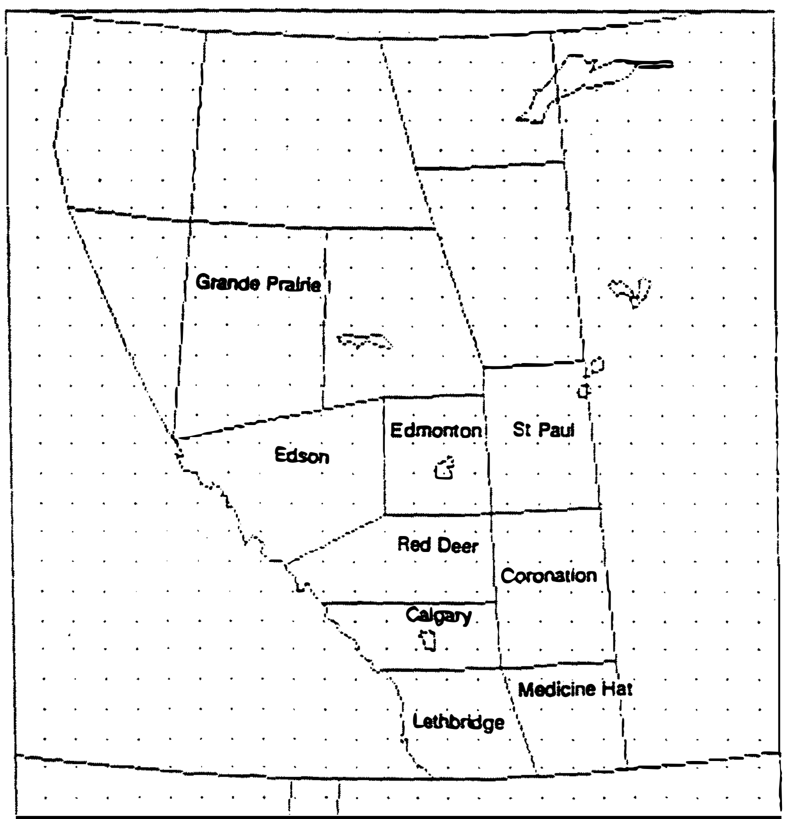

Figure 1.
Analysis and Display grid used for Moisture Flux Convergence diagnosis.

3. DISPLAY

When the analysis is complete, the display will appear on the screen. The values are contoured so that green shows positive moisture convergence (increasing moisture) and brown shows moisture divergence (drying). The zero line is shown in purple. Public forecast region boundaries, along with the cities of Edmonton and Calgary, are also displayed. The units of moisture convergence are in grams per kilogram per hour, or a rate of change of the mixing ratio. Values are contoured every .5 g $kg^{-1}hr^{-1}$. In other words, a center showing a value of +3.0 indicates that the instantaneous rate of change of moisture at the surface due to advection and convergence is an increase of 3 grams of water vapor per kilogram of air during the next hour. This of course does not take into account vertical transport of moisture, mixing from above an inversion, evapotranspiration, or precipitation, and hence cannot be used as an accurate predictor of dewpoints. However it is very useful for inferring tendencies of moisture and processes affecting a low level inversion. To visually interpret patterns of convergence and divergence, it may be useful to display the surface winds along with the convergence fields. To do this, press the 'W' key on the keyboard. This will also show which stations made it into the analysis. A station that was not included will not have its wind displayed when 'W' is entered.

Since the distance between SA stations can be as far as 300 km or more, mesoscale events are difficult to detect in data sparse areas. It seems rather odd then that what we are trying to forecast is the initiation of convective cells - definitely a mesoscale process. What this program will diagnose is areas or clusters of convective cells, and not individual cells. When looking at a plot on the lightning detector, one can see that thunderstorms usually do develop in lines or clusters. Note that since relatively sparse SA data is being used, one must be very careful to watch for possible errors in the derived field due to errors in the coding of the SA winds or dewpoint, local effects on the wind, or mesoscale processes such as convective wind gusts. If a thunderstorm is taking place over one of the stations, a convective wind gust will bias the analysis in the area of the station into thinking that the winds are stronger than they really are.

Displaying the winds and referencing the actual SAs will help to detect these errors. Most stations in B.C. are in deep valleys, and hence have their surface winds strongly influenced by topography. As a result, patterns in this area often show unrepresentative areas of convergence and divergence, and should be used with caution.

4. INTERPRETATION

Assuming that a good analysis takes place, many things can be interpreted from the display..

Look for persistent areas of convergence over time. This means that vertical motion and 'pooling' of low level moisture is taking place. If nothing has developed over about three hours of persistent convergence, the inversion may be about to break and rapid convective development may follow.

Thunderstorms tend to develop in areas of strong gradient between centers of divergence and convergence. This is because a strong cap will be formed in the divergence area which cannot be penetrated by the rising parcel. As moisture moves from the divergence area to the convergence area, it eventually reaches the point where the inversion has become weak or non-existent. It is at this point, where the gradient in convergence (and often moisture as well) is strong, that the storms develop.

Persistent or strong areas of divergence imply downward motion and warming in the boundary layer, resulting in a cap. Often the cap is strong enough that no convection will develop, even in a very unstable airmass.

The most favored area for development of severe weather appears to be the southeast quadrant of a well defined convergence maximum, especially if there is a divergence center nearby to increase the MFC gradient. See Figures 5 and 7.

A storm that has already developed can have its intensity influenced by surface convergence or divergence. If moving from a convergence area to a divergence area, the storm will most likely weaken, whereas a storm moving into strong convergence has the potential to develop rapidly.

The development of convection along the foothills can be detected several hours in advance if an axis of convergence appears parallel to the Continental Divide. What this is showing is the convergence produced not by convection, but by air rising up the eastern slopes as a result of daytime heating on the foothills. If the axis grows stronger in one spot, that is the most likely initiation area. In some cases, rapidly developing hailstorms in the foothills have been preceded for several hours by a strong convergence center immediately upstream. See Figure 6.

A convergence center coupled with a divergence center is usually more significant than a convergence center by itself, especially when the highest mixing ratios reside in the strongest gradient between the centers. The exception is when a single, strong, nearly circular area of moisture convergence appears. If the data surrounding the center is consistent, this is a favorable area for rapid supercell development. See Figure 8.

Persistence of areas of convergence and the rate of change in their strength are more important than the actual value of the center itself.

5. LIMITATIONS

There are several factors which may make the diagnosis of MFC unrepresentative, and the operational forecaster must be aware of them in order to interpret the data properly.

MFC is a surface parameter. It does not take into account what is happening aloft, although processes in the upper atmosphere may be reflected at the surface and appear in the diagnosis. Upper air analyses and forecasts must be used together with MFC to infer stability tendencies.

During the day, when the boundary layer is convectively mixed, MFC at the surface is fairly representative of what is happening through the entire boundary layer. However at night, when an inversion usually forms, boundary layer processes will be invisible at the surface. Convergence may still be taking place undetected in the boundary layer.

The analysis is only as good as the density and quality of data used to run it. With denser data and a finer grid, many new small areas of convergence appear that were previously not detectable. See Figure 8.

If a station has winds which are strongly influenced by local terrain, it can significantly bias the analysis in that area. This is often apparent in southern Alberta where strong west winds blow along the foothills, creating strong convergence areas between Lethbridge and Medicine Hat. Slave Lake and Drumheller also seem to have favored wind directions, which may lead to questionable analyses.

6. CASE STUDIES

There were many cases during 1990 in which MFC helped to identify favored convective areas. For brevity, only the surface moisture convergence fields will be examined. The Edmonton tornado of 1987 will also be examined on a 25 km grid.

6.1 July 6, 1990. Airdrie Tornado.

Figure 2 shows the MFC diagnosis at 1800 UTC July 6, 1990. There is a convergence center just west of Calgary, and another stronger center in the western Coronation region. Figure 3 shows the lightning detector display corresponding to 6 hours prior to and 12 hours after the diagnosis in Figure 2. Most of the activity did take place after 1800 UTC, so this diagnosis accurately depicted 12 hours in advance the area of most concentrated thunderstorm activity.

At 1940 UTC a tornado formed just north of Calgary.

By 2000 UTC (Figure 4) the convergence center near Calgary had weakened, but a strong center persisted further east, with a strong gradient of MFC in the southern Coronation region. At 2100 UTC (Figure 5) the center intensified further, while remaining nearly stationary. Two tornadoes touched down in the southern Coronation region, one at 2110 UTC and another at 2155 UTC. Of note in Figure 5 is the axis of convergence running exactly parallel to the foothills from near Calgary to Grande Prairie. There is no terrain in the diagnostic model, so what is displayed is a true reflection of an alteration of the wind field by the Rocky Mountains.

6.2 June 24, 1990. Large Hail near Calgary.

In Figure 6, a single very strong convergence area is seen southwest of Calgary. This center had persisted through much of the morning, but became even more evident at 1900 UTC as forestry data from the southern foothills was included. Golf ball sized hail was reported from three locations near Calgary at this time, and also later that afternoon.

6.3 September 16, 1990. Wind Damage near Edmonton.

Figure 7 shows the MFC field at 2100 UTC September 16, 1990. Of note is the very strong gradient of MFC in the southern half of the Edmonton region. Significant wind damage occurred to the roof of a large department store just south of Edmonton several hours later.

6.4 July 31, 1987. Edmonton Tornado.

In Figure 8, the analysis was performed with a 25 km grid resolution, and included forestry data. This allows for smoother contouring, but also picks up much more detail, especially in northern Alberta where forestry data adds a great deal of detail. There is a strong convergence center in the eastern Red Deer region, with the strongest gradient to the south of Edmonton. Two hours after this time, a tornado reaching F4 intensity struck Edmonton. This analysis demonstrates how data sparsity can influence the location of a convergence center on the analysis. The only stations available to diagnose the wind field south of Edmonton were Edmonton International, Red Deer and Coronation. Since the line of storms approached from the southwest, one would expect the convergence center to be further west as well. This may very well have been the case considering the data sparsity in that area.

6.5 Another use for the analysis scheme: Surface Vorticity.

Figure 9 is also a 25 km resolution analysis valid at 1900 UTC July 31, 1987. The only difference is that we are now computing surface vorticity:

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

By moving to a smaller grid spacing, higher values for vorticity are attainable. The center of maximum vorticity just south of Edmonton has a value of 20 X 10^{-4} s^{-1}. The strong center in southern Alberta, with a central value of 40 X 10^{-4} s^{-1} is primarily due to shear, as strong west winds were blowing in the southern Lethbridge region. The center near Edmonton is due more to curvature. Strong surface vorticity implies favorable conditions for generating rotation in updrafts. When combined with MFC, vorticity analyses may help narrow down even further the favored areas for severe convective development.

7. ADDITIONAL POSSIBILITIES

Other fields such as pressure, pressure tendencies, temperature, and temperature gradient may be analyzed on a sub-synoptic scale to infer boundary layer vertical motion and orographically induced vertical motion.

8. SUMMARY

The addition of several automatic weather stations over the coming years will allow us to diagnose features in the sub-synoptic scale. Faster computers will allow us to perform these analyses in real time. When interpreted carefully, the data from this denser network will reveal mesoscale processes. Moisture Flux Convergence is one of the mesoscale processes that we are now able to examine. When combined with other analyses, MFC can give valuable information about areas of preferred development of convective weather.

9. REFERENCES

Beckman, S., 1990: A Study of 12h NGM Low-level Moisture Flux Convergence Centers and the Location of Severe Thunderstorms/Heavy Rain. Preprints, 16th Conference on Severe Local Storms, Kananaskis, Alberta, American Meteorological Society, 78-83.

Nierow, A., 1989: An Evaluation of the NGM's Low-level Moisture Convergence Forecasts in Predicting Heavy Precipitation/Severe Weather. Preprints, 12th Conference on Weather Analysis and Forecasting, Monterey, American Meteorological Society, 626-630.

Waldstreicher, J., 1989: A Guide to Utilizing Moisture Flux Convergence as a Predictor of Convection. National Weather Digest, 14, 20-35.

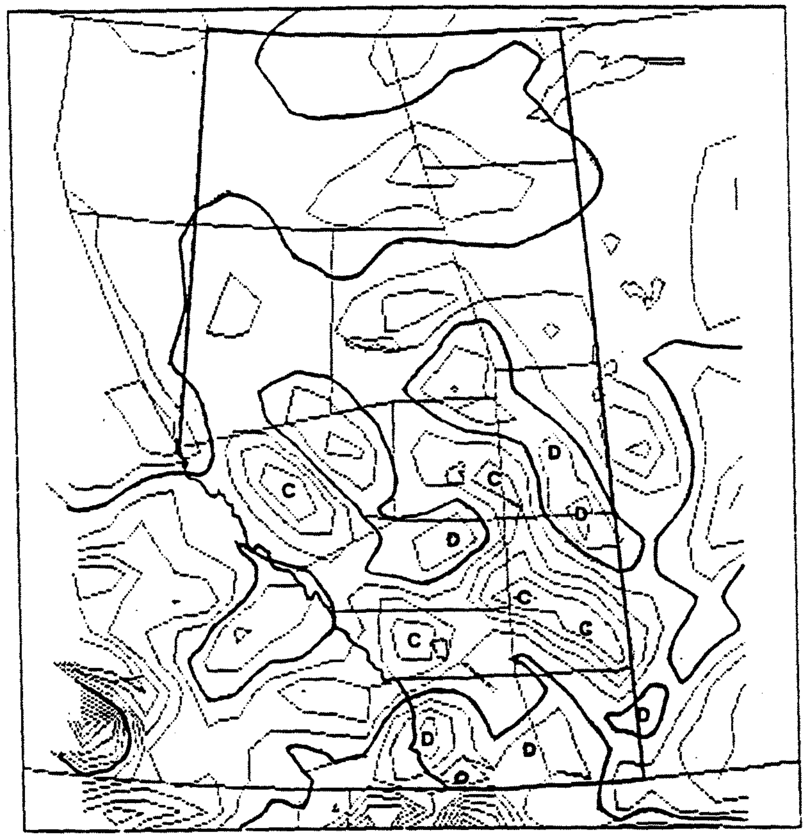

Figure 2. Moisture Flux Convergence Diagnosis for 1800 UTC July 6, 1990. Contouring interval is 0.5 g $kg^{-1}hr^{-1}$. Dark line is zero line.

Rapid development took place in convergence area west of Calgary. Convergence area in western Coronation region remained nearly stationary, indicating potential for further development to the east.

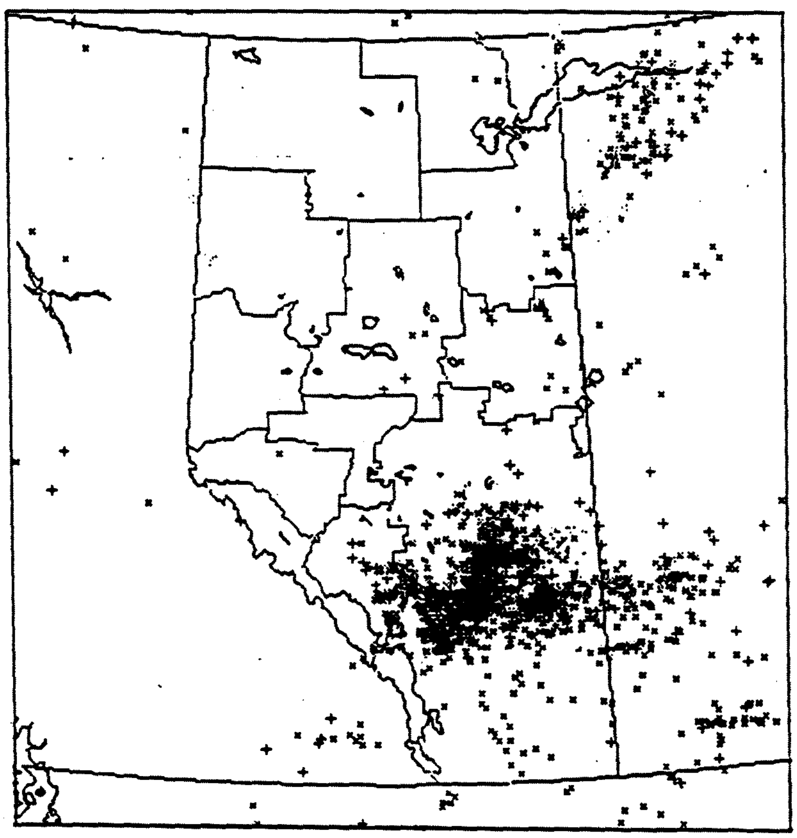

Figure 3. Lightning Detector Display for the period 1200 UTC July 6 to 0600 UTC July 7,1990.

Lightning activity is concentrated along convergence axis, and sharply diminishes in areas of divergence which were present south of Edmonton and in the St. Paul region.

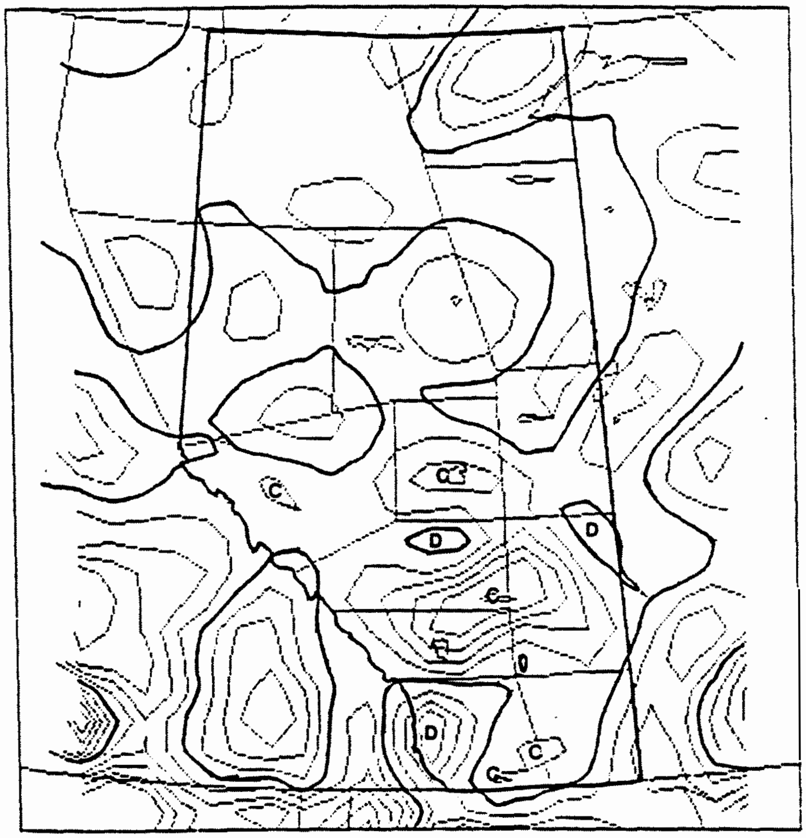

Figure 4. Moisture Flux Convergence Diagnosis valid 2000 UTC July 6, 1990.

Main center is in southeastern Red Deer region with axis remaining towards Calgary. A tornado had formed just north of Calgary 20 minutes earlier.

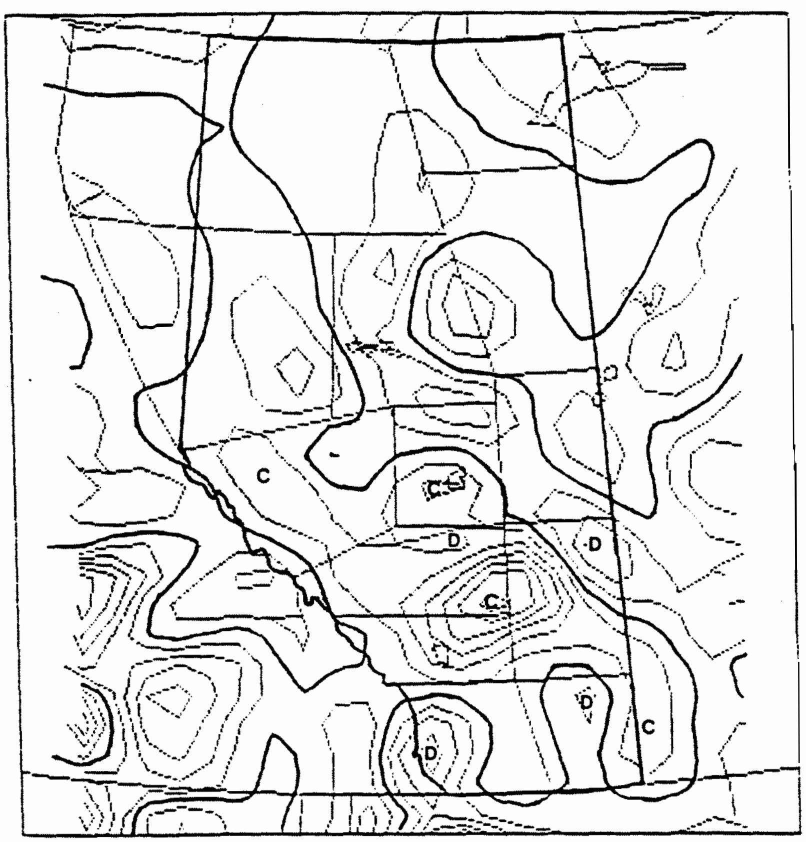

Figure 5. Moisture Flux Convergence Diagnosis valid 2100 UTC July 6, 1990.

Strong center of convergence has now persisted several hours in southeastern Red Deer region. At least two more tornadoes touched down during the next hour in the strong gradient area over southern Coronation region.

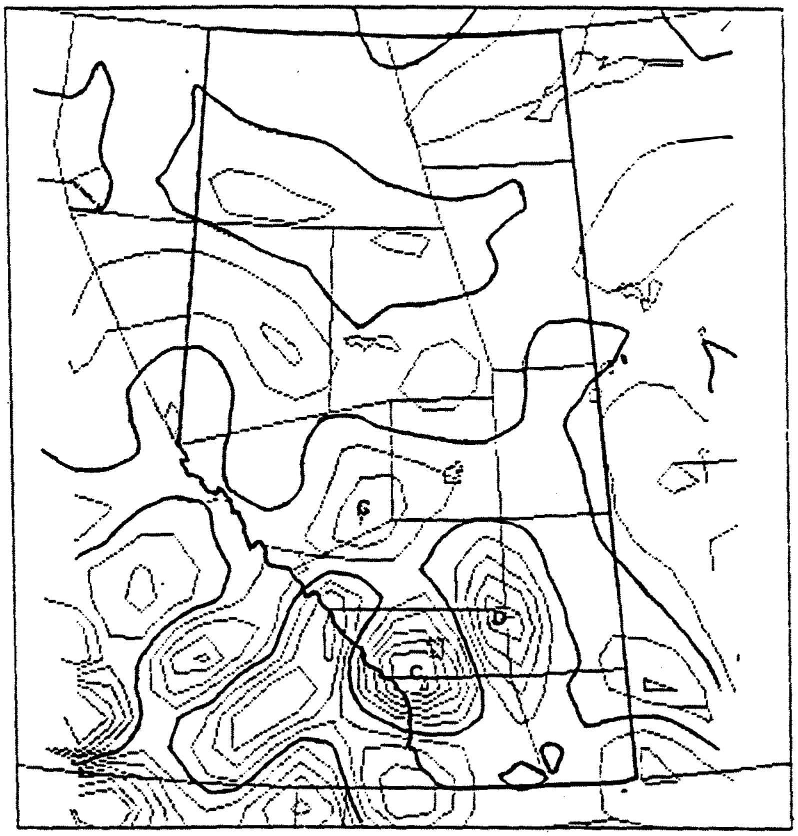

Figure 6. Moisture Flux Convergence Diagnosis valid 1900 UTC June 24, 1990.

A strong, nearly perfectly circular area of convergence appeared southwest of Calgary. Very rapid development followed, with golf ball size hail being reported near Calgary in the next hour. The cells moved east, but weakened once they encountered the area of divergence in western Coronation region.

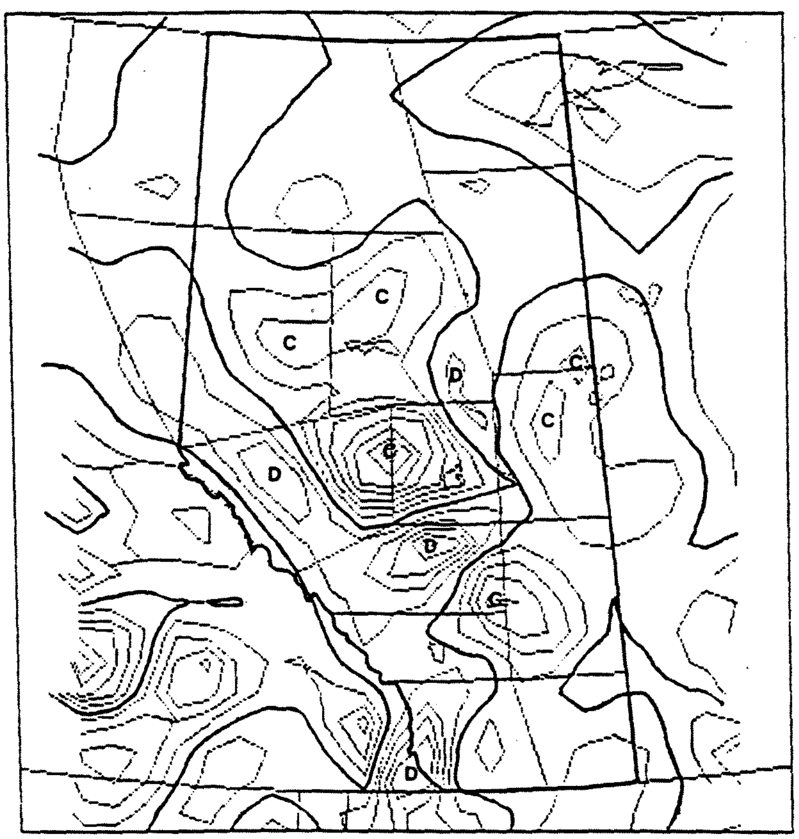

Figure 7. Moisture Flux Convergence Diagnosis valid 2100 UTC September 16, 1990.

A strong gradient in the MFC field existed southwest of Edmonton. A line of thunderstorms developed in this area and produced damaging winds just south of Edmonton several hours later.

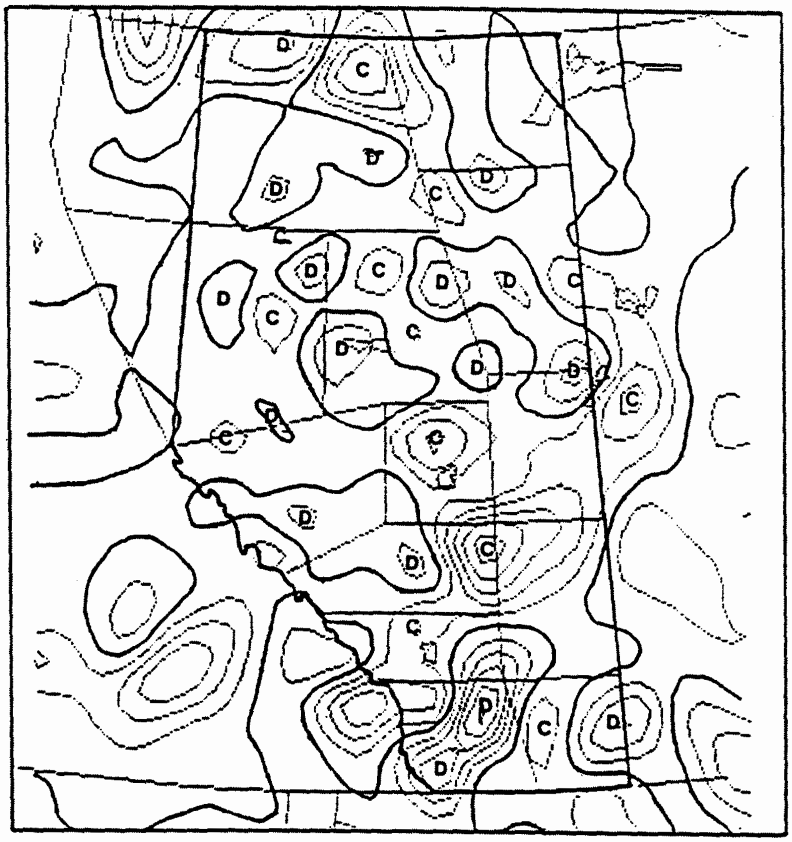

Figure 8. Moisture Flux Convergence Diagnosis valid 1900 UTC July 31, 1987. This was performed using forestry data on a 25 km grid.

A strong, nearly circular area of convergence appears southeast of Edmonton. The strong gradient area to the south of Edmonton is where the supercell initially developed, eventually producing an F4 tornado.

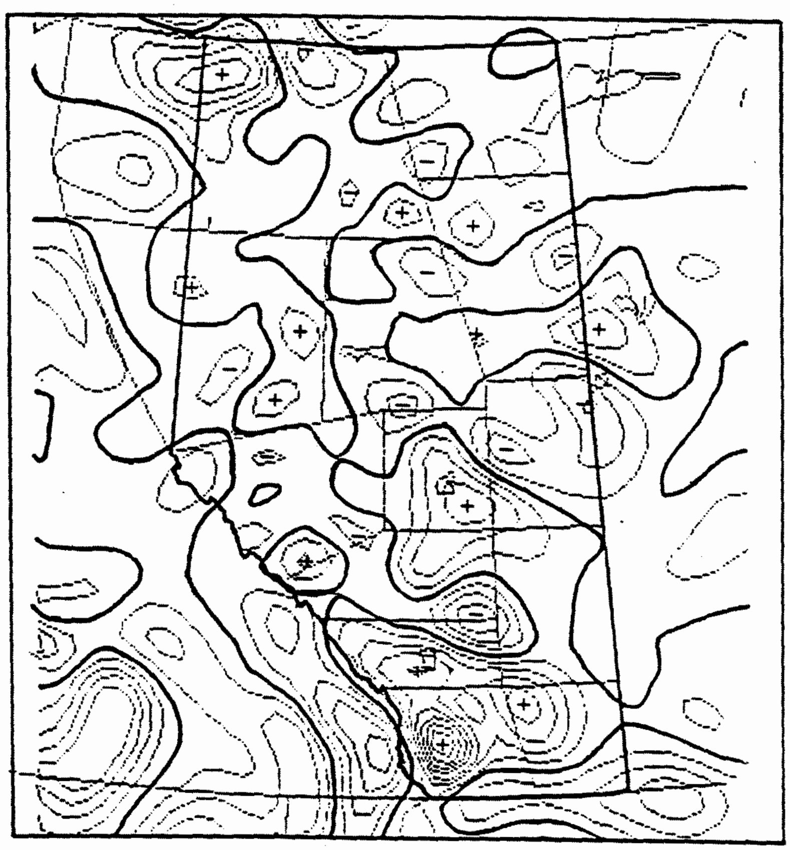

Figure 9. Surface Vorticity Diagnosis valid 1900 UTC July 31, 1987. Grid resolution of 25 km.

A strong vorticity center appears just southeast of Edmonton. Contour interval is 5 X 10^{-4} s^{-1}.

WESTERN REGION FIRE WEATHER COMMITTEE

TERMS OF REFERENCE

PREAMBLE

The 1975 Federal Department of the Environment (DOE) Policy on Meteorological Services for Forest Fire Control set out the responsibilities of the Atmospheric Environment Service (AES) and the Canadian Forestry Service (CFS) in provision of fire weather forecasts, fire danger forecasts, and other weather-related services to the various fire control agencies. Briefly, this policy gave AES the responsibility of providing current and forecast fire weather and Fire Weather Indices in accordance with the needs of fire control agencies. The CFS role was that of research and development of improved Indices, research on fire behavior relationships with weather factors, and cooperation with AES in preparation of training aids and manuals. Both AES and CFS shared the responsibility of improving meteorological services for fire control in Canada.

In 1976, six regional committees were formed to facilitate the implementation of the DOE Policy on Meterological Services for Forest Fire Control. These committees were aligned on the basis of the existing AES administrative boundaries, namely: **Pacific** (British Columbia), **Western** (Alberta, Yukon, and the Northwest Territories), **Central** (Saskatchewan, Manitoba, and Northwestern Ontario), **Ontario**, **Quebec**, and **Atlantic** (Nova Scotia, New Brunswick, Newfoundland, and Prince Edward Island).

The transfer of CFS to Agriculture Canada in 1985, the subsequent creation of the new Department of Forestry (Forestry Canada) in 1988, and the development of a new AES policy on meteorological services to forestry to replace the 1975 DOE policy have superseded the earlier federal mandate for regional fire weather committees. Since then, the committees have continued regular meetings with the general goals of ensuring that working-level cooperation continues among agencies involved in fire weather services, and providing benefits through the timely exchange of new information on a regular basis.

STATEMENT OF PURPOSE

The Western Region Fire Weather Committee (WRFWC) is a working group of federal, provincial, and territorial government agency representatives directly involved in the development and communication of fire weather-related information and forest fire management decision-aids within the Western region. The WRFWC exists to aid inter-governmental exchange of services and information related to the provision and exchange of services and information related to the provision and use of fire weather information services; to review and recommend technical alternatives to specific problems; and to recommend administrative procedures in the management of the respective government fire weather programs. The WRFWC does not routinely report to the executive levels within its member agencies, although it may approach and make recommendations to such levels in order to expedite improvements to fire weather services in the region.

MEMBERSHIP

Western Region Defined

For the purposes of the WRFWC, the Western region consists of Alberta and the Northwest Territories. To ensure information exchange and coordination of meteorological information services across political borders among member agencies, affiliate membership, meeting attendance and exchange of meeting minutes is encouraged between the WRFWC and the adjacent Pacific Region Fire Weather Committee and the Central Region Fire Weather Committee.

Member Agencies

Forestry Canada (Northern Forestry Centre)

Two members usually serve on the WRFWC. Responsibilities include research and technology transfer with respect to fire meteorology and climatology, and all aspects of the development and implementation of the Canadian Forest Fire Danger Rating System (CFFDRS).

Atmospheric Environment Service (Western Region)

Members representing the Alberta Weather Centre and the Arctic Weather Centre weather forecasting units, scientific services, and general weather services. Responsibilities include the provision of fire weather and air quality forecasts and weather data to assist fire management agencies with wildfire control and prescribed fire and smoke management, as specified in policy documents and/or individual agreements as may be negotiated or implemented from time to time; supporting meteorological research and development activities.

Alberta Forest Service (Provincial Headquarters)

Members representing components within the Forest Protection Branch. The Alberta Forest Service is a primary user of the fire weather-related information and decision support systems provided by Forestry Canada, Atmospheric Environment Service, and the Alberta Forest Service's weather section. Through the Forest Protection Branch, a key link exists between providers of the fire weather information and its ultimate application at the provincial and field level for activities such as wildfire prevention, preparedness, suppression and prescribed fire planning and operations. Industry (forest management licensees) is a direct provider and user of fire weather information at the field level as well, but, generally, the Alberta Forest Service provides a regulatory link in the system. The Alberta Forest Service forests and districts are principal sources of fire weather data to the provincial fire weather network.

Northwest Territories Department of Renewable Resources (Territorial Forest Fire Centre)

Members representing components within the Fire Management Division of the Government of the Northwest Territories Department of Renewable Resources. The Fire Management Division, headquartered at the Territorial Forest Fire Centre in Fort Smith, is a primary user of the fire weather-related information and decision support systems provided by Forestry Canada, Atmospheric Environment Service, and the Territorial Forest Fire Centre. Through the Territorial Forest Fire Centre, a key link exists between providers of the fire weather information and its ultimate application at the territorial and field level for activities such as wildfire prevention, preparedness, suppression and prescribed fire planning and operations. The Department of Renewable Resources Areas/Districts are the principal sources of weather data to the territorial fire weather network.

Parks Canada (Prairie and Northern Region, Western Region)
(Statement to be developed by Parks Canada)

Limits on Membership

In order to confine its role to matters affecting intergovernmental provision of fire weather services to government and industry in the Western Region, membership is restricted to the above-named government agencies and industry representatives. However, the WRFWC will freely consult other government agencies and private sector firms and organizations in its normal activities, and may invite such persons to attend specific meetings where representations can be made to committee as required.

STRUCTURE AND OPERATIONAL PROCEDURES

Executive Structure and Meeting Format

The WRFWC "elects" one of its member agencies to act as executive (chairperson and secretary) for a two-year period, usually on a rotating basis. The executive calls and hosts meetings as required, usually once per year in the late winter or early spring. Minutes of the meetings are produced by the executive, circulated in draft form among member agencies, and in final form to all members, with a copy to the Pacific Fires Weather Committee and to the Central Fire Weather Committee.

Seminars

In conjunction with the regular annual meeting of the WRFWC, the executive may call and host a seminar session, usually once every two years. The seminar sessions are presented to enhance the exchange of information and transfer of technology among its membership. To this end, and in addition to the member agencies, educators for Universities and Technology Schools within the region, researchers doing fire-related studies, and industry representatives will be actively solicited to make presentations and to attend the seminar.

PREVIOUS PROCEEDINGS IN THE WESTERN REGION FIRE WEATHER COMMITTEE SCIENTIFIC AND TECHNICAL SEMINAR SERIES

Alexander, M.E. (compiler and editor). 1983. Proceedings of the First Western Region Fire Weather Committee Scientific and Technical Seminar, March 22, 1983, Edmonton, Alberta. Gov. of Canada, Can. For. Serv., Nor. For. Res. Centre, Edmonton, Alta. File Rep. No 10. 11 pp.

- Fifteen years of philosophical examination on fire and weather -- R.E. Schmidt
- Alberta's geographical position in relation to fire weather -- B. Janz
- Historical fire weather analysis -- C.A. White, K. Baker, and J. Kellas
- Breakdown of the upper ridge pattern associated with extreme fire behavior in Alberta -- N. Nimchuk
- Fire behavior in the black spruce-lichen woodland fuel complex: the Porter Lake project -- M.E. Alexander

Alexander, M.E. (compiler and editor). 1985. Proceedings of the Second Western Region Fire Weather Committee Scientific and Technical Seminar, March 6, 1984, Edmonton, Alberta. Gov. of Canada, Can. For. Serv., Nor. For. Res. Centre, Edmonton, Alta. File Rep. No 10. 29 pp.

- A comparison of the fire-weather severity in Northern Alberta during the 1980 and 1981 fire seasons -- D.A. Harvey
- Prescribed fire in Banff National Park: a case study -- C.A. White
- Downslope forest fire spread: the Torrens example -- T.A. Van Nest
- Wildfire documentation in the Northwest Territories: a case study of Fort Simpson-40-1983 -- R.A. Lanoville and R.E. Schmidt
- The Ash Wednesday bushfires of 16 February 1983 in South-eastern Australia: video tape -- overview by M.E. Alexander

Alexander, M.E. (compiler and editor). 1986. Proceedings of the Third Western Region Fire Weather Committee Scientific and Technical Seminar, February 4, 1986, Edmonton, Alberta. Gov. of Canada, Can. For. Serv., Nor. For. Res. Centre, Edmonton, Alta. File Rep. No 10. 30 pp.

- On the effect of wind shear and atmospheric stability on forest fires -- E.R. Reinelt

- Development of a preparedness system for forest fire initial attack in the Northwest Territories -- R.A. Lanoville

- The 1950 Chinchaga River fire in the Peace River region of British Columbia/Alberta: preliminary results of simulating forward spread distances -- P.J. Murphy and C. Tymstra

There were no proceedings for the Fourth or the Fifth Western Region Fire Weather Committee Scientific and Technical Seminars.

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