

# **Proceedings of the Eighth Central Region Fire Weather Committee Scientific and Technical Seminar**

April 3, 1992  
Winnipeg Manitoba

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FORESTRY CANADA  
NORTHWEST REGION  
NORTHERN FORESTRY CENTRE  
1993

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Front Cover: Comparison of two people-caused fire arrival prediction models, Northwestern Region, Ontario, 1989.



## **INTRODUCTION**

The Central Region Fire Weather Committee (CRWFC) currently holds two meetings each year. Annual business meetings, which started in 1976, are usually held between the months of November and January, while the Technical Sub-Committee, formed in 1983, meets in April. The CRWFC member agencies include:

Atmospheric Environment Service, Central Region  
Forestry Canada, Northwest Region  
Manitoba Natural Resources  
Ontario Ministry of Natural Resources (sub-committee participants only)  
Parks Canada, Prairie and Northern Region  
Saskatchewan Parks and Renewable Resources

In conjunction with the Technical Sub-Committee meetings, a half-day Scientific and Technical Seminar is usually conducted. The goal of these sessions are to reacquaint meteorologists required to make fire weather forecasts with the problems associated with forest fire. These sessions provide excellent opportunities for foresters and meteorologists, both in operational and research aspect, to gather and present their current work.

This particular session has focused on the theme of forest fire occurrence. The ability to estimate the risk of forest fires is every bit as important as estimating fuel moisture and modelling fire behavior and, until recently, this aspect of fire science has been relatively ignored. The papers in these proceedings manage to cover most aspects of fire occurrence prediction. I hope that you find these papers a helpful introduction to the subject.

Kerry Anderson  
CRWFC Seminar Coordinator



# **FORECASTING LIGHTNING OCCURRENCE AND FREQUENCY<sup>1</sup>**

by Kerry Anderson<sup>2</sup>

## **ABSTRACT**

Lightning is one of the most common severe weather events, yet, is perhaps the hardest to forecast accurately. This paper reviews the physics of lightning, factors that lead to intense lightning activity, and models that have been developed to forecast lightning occurrence and frequency.

## **INTRODUCTION**

Lightning is one of the most spectacular meteorological phenomenon and the most common severe weather to affect mankind directly. But despite decades of research and advances in instrumentation, the exact origin of lightning and the mechanisms behind the charge buildup within a thundercloud are still not understood (Dye 1990; Williams 1988; Krider and Alejandro 1983).

The problem confronting lightning research is the range of scales the phenomena encompass. Processes at the molecular level must be combined with those scaling the depth of the troposphere and greater. Though progress has been made to understand specific processes, putting these together into the big picture has eluded the research community.

Without a firmly established understanding of the principles behind cloud electrification, weather forecasters have only a superficial knowledge of lightning. They know that lightning is generally associated with convective activity and it has been assumed that methods of predicting other convective phenomena, such as rain showers and hail, should work well for predicting lightning. As a result, only a few predictive techniques have been devised to forecast lightning specifically (Sly 1965; Fuquay 1980; Andersson 1989; Anderson and Charlton 1990; Anderson 1991).

In the last decade, lightning detection systems have given meteorologists a new source of data. These systems provide real time data of lightning occurrence and its location. But, like a Pandora's box, lightning detection systems have created more questions than answers, as observers begin to look at lightning with a new degree of resolution.

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Is the intensity of lightning activity directly correlated with the intensity of convection? Observations do not seem to support this. The experience in Alberta is that although indicators of convective instability point to thunderstorm activity, there is no way of determining whether a storm will yield 1,000 or 10,000 lightning flashes (Nimchuk 1985).

The forest sector has a definite need for lightning forecasts as lightning is a major cause of forest fires. Starting 34%<sup>3</sup> (3,101) of the near 10,000 fire occurrences annually in Canada, lightning-caused fires account for 87% (1,840,822 ha) of total area burned nationwide. The discrepancy in the percentages is due to the general inaccessibility of lightning-caused fires. As a result, a large number of them escape the initial containment attempts. For this reason, forest protection agencies are one of the main users of lightning detection systems.

This paper reviews the physics of lightning. It discusses the thundercloud, charge generation, and the lightning flash, and lightning detection. This paper also reviews models that have been developed to forecast lightning occurrence and frequency.

## **THE PHYSICS OF LIGHTNING**

This section provides a brief overview of the basic theories and observations of thundercloud electrification and the lightning discharge. For a comprehensive background, the reader is referred to textbooks by Chalmer (1967), Uman (1969; 1987), and Golde (1977), and review papers by Latham (1981), Uman and Krider (1982; 1989), and Williams (1985).

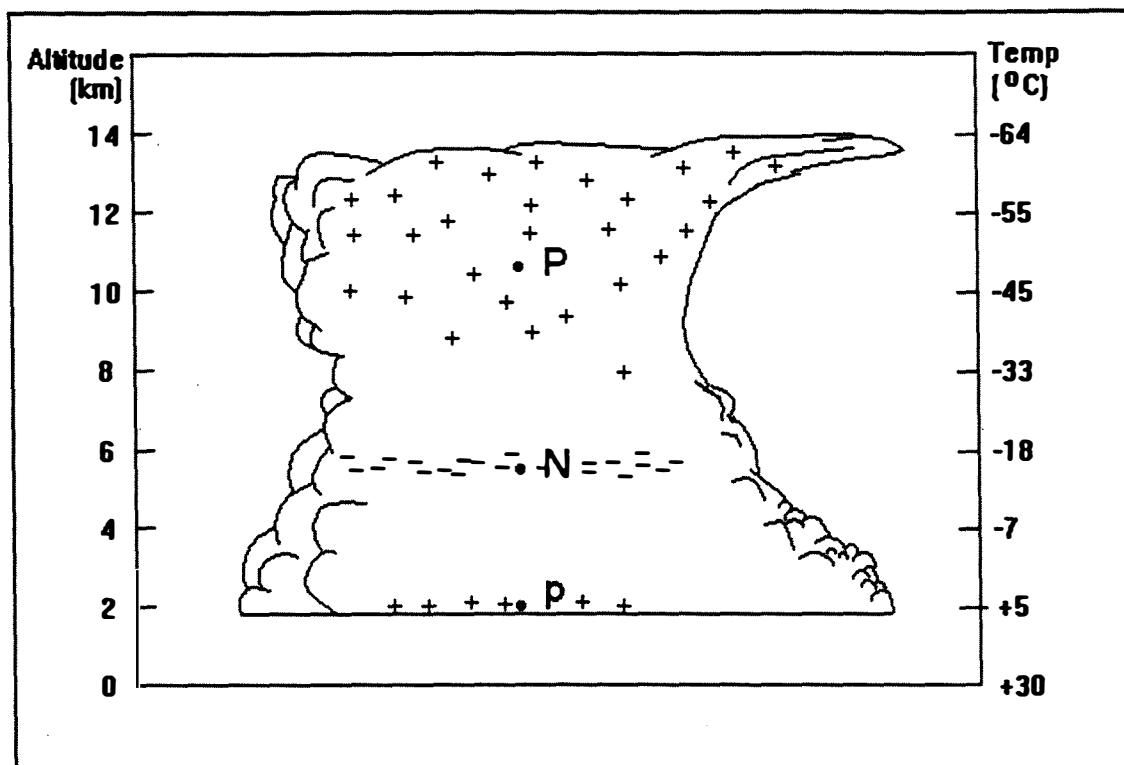
### **Thunderstorm Structure**

Lightning is associated with convective activity. Thunder (and thus lightning) is used by the professional weather observer to classify the severity of convective activity. Cumulonimbus clouds are the largest form of convective cloud and typically produce lightning. Cumulonimbus clouds with lightning activity are generally referred to as thunderclouds.

The classical thundercloud model was developed in the 1920s by Wilson (1920; 1926) from ground-based electric field measurements. It consists of a positive electric dipole (a positively charged region above a negatively charged region). Further research using balloon measurement identified an additional weak region of positive charge at the cloud base (Simpson and Scrase 1937; Simpson and Robinson 1941). This double-dipole structure, as shown in figure 1, has been confirmed with electric field measurements both inside and outside the cloud. Because of the weak strength of the lower charge region, both the positive dipole and the double-dipole can be used to describe the general structure of a thundercloud.

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<sup>3</sup>Figures based upon a ten year annual average for 1973 to 1982 for the ten provinces and two territories (Ramsey and Higgins 1986).



**Figure 1.** Typical charge distribution within a thundercloud.

The three centres of accumulated charge are commonly labelled p, N, and P. The upper positive centre, P, occupies the top half of the cloud. The negative charge region, N, is located in the middle of the cloud. The lowest centre, p, is a weak, positively charged centre at the cloud base. The N and the P regions have approximately the same charge, creating the positive dipole. Malan (1963) documented charges and altitudes above ground level for the p, N and P regions of a typical South African thundercloud (1.8 km ASL) as +10 C (coulombs) at 2 km, -40 C at 5 km, and +40 C at 10 km. These are representative of values that can vary considerably with geography and from cloud to cloud.

Research by Krehbiel *et al.* (1983; 1984), and MacGorman (1981) on the charge structure of lightning discharges has gone further to identify the nature of the negative charge region. Krehbiel's study centered on two thunderstorms that developed over Florida. In the study, Krehbiel used LDAR (lightning detection and ranging) and acoustic location to locate the sources of lightning discharges within the cloud. Doppler radar was used to define the wind-fields and areas of precipitation. General findings indicate that the negative charge region within a thundercloud is located within a subfreezing region of relatively small vertical dimension (less than a kilometre) somewhere between -10 and -25 °C (Krehbiel *et al.* 1983). Krehbiel further notes that the altitude of the negative charge centre remained constant throughout the storm growth and was not affected by the strength of the vertical wind.

There is a general association between radar reflectivity and negatively charged lightning flashes. Lightning discharge sources are located near, but not necessarily within, the area of highest

reflectivity (MacGorman *et al.* 1983). This is supported by Mazur (1983) and Mazur and Rust (1985). In two studies of thunderstorms developing off Wallops Island, Virginia, Mazur found that the region of maximum flash density was close to the leading edge of the precipitation core, defined by 50 dBZ weather radar reflectivity. Though Mazur did not state the polarity of these flashes, it is inferred that they come from the negative charge centre. Lopez, Otto, Ortiz, and Holle (1990) also observed that, in a Colorado thunderstorm, the peak lightning activity occurred in the gradient areas of high reflectivity.

The positive charge region higher up in the cloud tends to follow a different set of characteristics. Krehbiel's study (1983, 1984) noted that the positive charge region did rise steadily with time at a speed of approximately 8 m/s, suggesting that positively charged particles are carried by the updrafts within the cloud. MacGorman *et al.* (1984) noted that positive flashes occurred most frequently in the mature to late stages of growth in individual convective cells. He also noted that these flashes tended to occur in the forward swept anvil of the cloud and the stratiform layer following the cell. These observations have been supported by a number of other studies (Holle 1985; Stolzenburg 1990; Lopez, Ortiz, Augustine, Otto, and Holle 1990; Holle *et al.* 1990; Hunter *et al.* 1990). This would suggest that the positively charged particles are carried by the convective currents in the cloud and positive flashes are more likely to occur when the charge region is horizontally displaced from the negatively charged region.

### **Theories of Charge Generation in Thunderclouds**

Several theories have been developed to explain the charge generation within a thundercloud. To be valid, these theories must be consistent with thunderstorm observations. Mason (1953; 1971) outlined such a list of conditions and parameters. These are:

1. The average duration of precipitation and electrical activity from a single thunderstorm cell is about 30 minutes.
2. The average electric moment destroyed in a lightning flash is about 100 C km, corresponding to charge of 20-30 C.
3. In a large, extensive cumulonimbus, this charge is generated and separated in a volume bounded by the  $-5^{\circ}\text{C}$  and the  $-40^{\circ}\text{C}$  levels and having an average radius of perhaps 2 km.
4. The negative charge is centred near the  $-5^{\circ}\text{C}$  isotherm, while the main positive charge is situated some kilometres higher up; a secondary positive charge also may exist near the cloud base, being centred at or below the  $0^{\circ}\text{C}$  level.
5. The charge generation and separation processes are closely associated with the development of precipitation, probably in the form of soft hail.
6. Sufficient charge must be generated and separated to supply the first lightning flash within 12-20 minutes of the appearance of precipitation particles of radar-detectable size.

There are two general theories to explain the charge buildup required to electrify a thundercloud. They are the convective theory and the gravitational theory.

The convective theory proposes that free ions in the atmosphere are captured by cloud droplets and then are moved by the convective currents in the cloud to produce the charged regions. Vonnegut (*in* Golde 1977) proposed a positive feedback mechanism where positive ions released into the lower atmosphere by corona discharge are caught in the updrafts of a developing cumulus cloud. When raised to the upper region of the cloud, the net positive charge attracts negative ions in the upper atmosphere along the cloud's exterior. In turn, these negative ions are lowered by environmental downdrafts surrounding the cloud to produce the lower negative charge centre.

There are problems with Vonnegut's theory. The travel time required for the positive ions to reach the upper cloud regions is twenty minutes or more - too long for the charge build-up needed to create the breakdown fields for lightning initiation (Latham 1981). A second, and more serious problem with the convective theory is the incompatibility with the stratified, motionless characteristic of the negative charge region found by Krehbiel *et al.* (1983, 1984). If vertical air motions are expected to produce the charge regions, they should have a pronounced vertical dimension corresponding to the regions of strongest updraft and downdraft. Krehbiel found that the positive charge did rise with time. This does show the importance of convective currents in the cloud, though it does not necessarily support Vonnegut's model.

The gravitational theory assumes that negatively charged particles are heavier and are separated from lighter positively charged particles by gravitational settling. For the gravitational theory to work, there must be some charge exchange process between particles of different sizes. Charge can be exchanged between particles by inductive and non-inductive processes. Dye (1990) and Illingworth (1983) provide comprehensive reviews of these processes.

The inductive process assumes that charge is exchanged between colliding particles polarized in an electric field (see Figure 2). Particles are polarized by the fair weather electric field. When a cloud particle collides but does not coalesce with the underside of a falling precipitation particle, negative charge is transferred from the precipitation particle to the cloud particle. This results in a positive charge on the light cloud particle and a negative charge on the heavier precipitation particle.

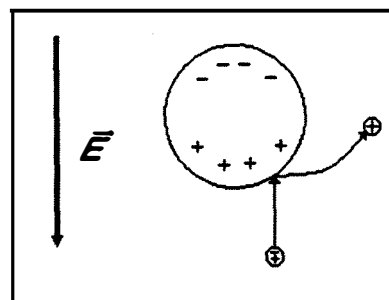


Figure 2. The inductive process.

The appeal of the inductive process is that it sets up a positive feedback system originating from the fair weather electric field.

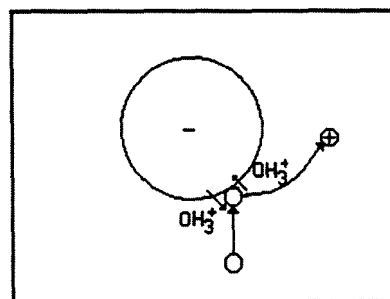
As the regions of charged particle separate, the thunderstorm's electric field is intensified. In turn, this increases the degree of polarization in the remaining particles and the efficiency of charge exchange process.

For inductive processes to be feasible, several problems must be addressed. Particles must collide so that coalescence does not occur. The collision must be in alignment with the dipole moment to exchange charge efficiently (which falls off as the cosine of the angle of deviation

from the dipole moment). They must remain in contact long enough for significant amount of charge to be exchanged. Collisions involving water particles tend to coalesce and when they do not, either the angle of contact is not in alignment with the dipole moment or the contact time is not long enough to exchange a significant charge. Collisions involving ice particles are more efficient as coalescence is less likely but whether enough charge can be exchanged by this process is debatable.

The non-inductive process assumes that charge can be exchanged independent of external electric fields. The most promising is the non-inductive exchange between ice crystals and hailstones, referred to as the ice-ice process, first proposed by Reynolds *et al.* (1957).

The effectiveness of the ice-ice process lies in the thermo-electric properties of ice (see Figure 3). The mobility of the  $(OH_3)^+$  defect in ice is greater than the  $(OH)^-$  defect and the number of defects increase with temperature. When warm and cold ice particle come in contact, the positive defect flows faster from the warmer to the colder particle than the converse giving the colder particle a net positive charge. Therefore in the typical scenario, a warm hailstone or snow pellet will acquire a net negative charge as it falls through a region of cold ice crystals.



**Figure 3.** The non-inductive ice-ice process.

Williams (1988) further notes there exists a charge-reversal level where at warmer temperatures, the hailstone becomes positively charged and ice crystals negatively charged. Speculation about the exact temperature of the charge-reversal level is still in dispute, though observations would suggest it is near  $-15^{\circ}\text{C}$ .

The problem with collision processes, and all thundercloud charge generation models in general, is the time and the precipitation rate required to generate the necessary electric fields. The first lightning flash usually occurs within 20 minutes of the formation of precipitation within the cloud. The inductive and non-inductive processes described above do approach the required electric field strengths to initiate lightning but generally fall short by about a magnitude of ten (Williams 1985). Mathpal and Varshneya (1983) calculated the electric field strengths produced by these processes at various precipitation rates. They concluded that alone, neither of these processes could account for the necessary charge build-ups. They went further to calculate combined processes and concluded that a combined induction and convection was most favourable.

Theories of thundercloud charge generation is still very speculative. The favourability of one process over another has fluctuated over time due to the inadequate number of laboratory experiments and scarcity of useful field observations (Latham 1981; Williams 1985). *One clear conclusion is that there is no unique mechanism to generate the required charge under all conditions.* For example, the ice-ice process, presently the most favoured (Dye 1990) does not explain warm cloud lightning, albeit a not too frequent event. As research develops, the most likely explanation will lie in a combination.

## The Lightning Flash

The charge buildups in thunderclouds are unstable. When electric fields generated by the charge buildups becomes too strong - typically  $3\text{--}4 \text{ kV cm}^{-1}$  at the altitude of the negative charge region of the cloud (Latham 1981) - electrical breakdown of the air occurs and charge is exchanged within the cloud or to the ground. Charge is exchanged by a lightning flash.

Lightning can occur in four ways. Lightning can travel between points within a cloud, from a cloud to clear air, from a cloud to an adjacent cloud, and from a cloud to ground. These flashes are referred to as intracloud, cloud-to-air, cloud-to-cloud, and cloud-to-ground, respectively.

Intracloud (IC) flashes, redistributing the charge within the cloud, account for over half the lightning flashes in northern latitudes (Uman and Krider 1989). Cloud-to-cloud and cloud-to-air flashes are less common. Besides aviation, these three types of flashes have little impact on man.

Cloud-to-ground (CG) flashes are very common and have been well documented. They exchange charge between the cloud and ground. These flashes affect man greatly, causing injury and death, disrupting power and communications, and igniting forest fires. Because of these impacts, the cloud-to-ground flash has been the topic of much research.

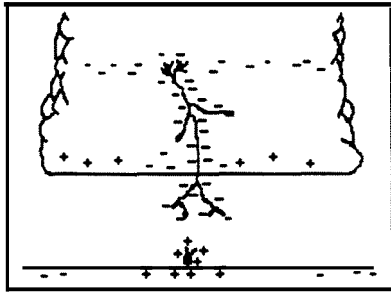
The cloud-to-ground lightning flash can lower positive (+CG) or negative (-CG) charge, depending on the source of the flash. This can be determined by the polarity of the stroke's current. Characteristics of negative and positive cloud-to-ground flash are summarized in table 1 (Uman 1987).

**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 ( $\mu\text{sec}$ )	30	230
Average number of strokes	3-4	1
% containing long continuing current	20	80

The negative cloud-to-ground lightning flash can be broken down into three stages. The stepped leader, the return stroke, and the dart leader.

The stepped leader is a small packet of negative charge that descends from the cloud to the ground along the path of least resistance (see Figure 4). In its path, the leader leaves a trail of ionized gas. It moves in steps, each typically tens of metres in length and microseconds in duration. After a step, the leader pauses for about 50 microseconds, then takes its next step. The

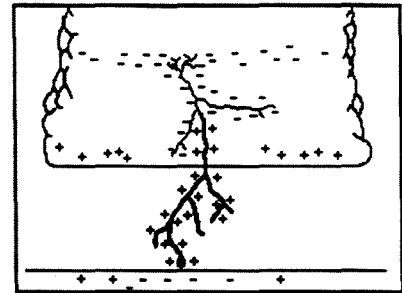


**Figure 4.** The stepped leader.

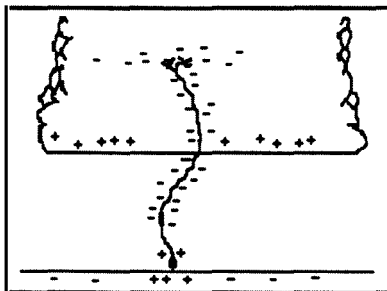
leader charge packet sometimes breaks up to follow different paths, giving lightning its forked appearance.

As the stepped leader approaches the ground, electrons on the surface retreat from the leader creating a region of positive charge. Corona discharges (dielectric breakdowns in the air, also known as *St. Elmo's Fire*) are

released from tall objects on the surface and reach out to the approaching leader. When the downward moving leader connects with a surface corona discharge, a continuous path between the cloud and the ground is established and a powerful return stroke is triggered (see Figure 5). The return stroke rapidly moves as a wave upwards into the cloud following the ionized trail of the stepped leader, stripping the electrons from its path.



**Figure 5.** The return stroke.



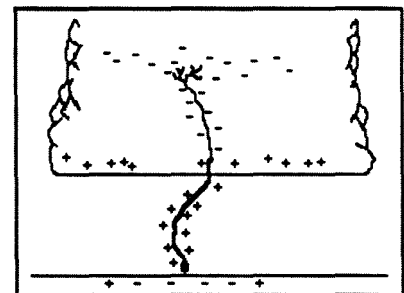
**Figure 6.** The dart leader.

After the return stroke, the lightning flash may end or, if enough charge in the cloud is collected, a dart leader may come down from the cloud following a direct path to the surface (Figure 6). In turn, the dart leader triggers a second return stroke (Figure 7).

A single lightning flash can be comprised of several return strokes. The average number of return strokes in a lightning flash is 3 or 4, each stroke typically separated by 40 to 80 milliseconds.

The positive cloud-to-ground flash is less common than the negative. Coming from higher altitudes in the cloud, positive flashes make up about 10% of all lightning flashes (Uman and Krider 1989). They are usually composed of a single stroke, and have longer, continuing currents (see Table 1). From the forestry perspective, positive flashes are of more concern as the longer currents are more likely to start fires (Fuquay 1972).

Several studies have concentrated on the characteristics of the positive flash but results are inconclusive due to the number of observations. The percentage of positive flash appears to increase with latitude (Takeuto *et al.* 1983) and with the height of local terrain (Uman and Krider 1989). Also, positive flashes are more common in winter storms (Takeuto *et al.* 1983; Williams 1985). The apparent cause for this is that the lower freezing level places the positive charge centre closer to the ground thus increasing the likelihood of a flash.



**Figure 7.** The second return stroke.

Positive flashes are more common in stratiform clouds while negative flashes tend to occur in areas of strong convection (Holle *et al.* 1988). Also, thunderstorms that predominantly consist

of negative flashes in their early stages, often end with positive discharges as the storm matures and the anvil spreads out (MacGorman *et al.* 1984).

A popular theory is that horizontal wind shears force a tilting of the dipole axis providing a route for the positive flash (Takeuto *et al.* 1983; Rust and MacGorman 1985; Takagi *et al.* 1986) but this has yet to be shown conclusively.

### Lightning Detection

Most forest and weather services now use the wide band magnetic gate design lightning detector (Krider *et al.* 1980; 1976) manufactured by Lightning Location and Protection Inc. (LLP) of Tucson, Az. The LLP lightning detection system determines the time and location of a lightning flash by triangulating information from 12 direction finder stations situated in and around the province (see Figure 8). These data are stored on magnetic tape. Maps can be processed to show the location and polarity of lightning flashes that occur over a period of time (see Figure 9).

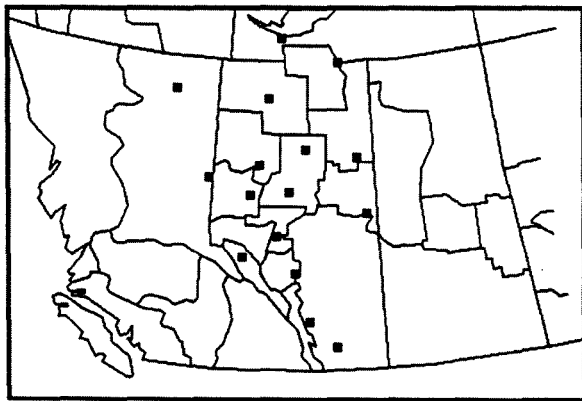


Figure 8. The Alberta Forest Service's LLP direction finder network.

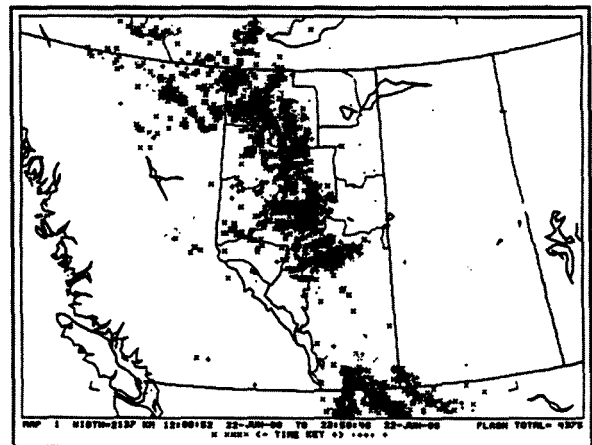


Figure 9. Lightning detection map for June 22, 1988.

The LLP lightning detection system has three components: the direction finder, the position analyzer and the remote display processor.

The direction finder (DF) senses the electromagnetic field radiated by a lightning flash using two erect, orthogonal wire loop antennas and a horizontal flat plate antenna. The antenna's bandwidths are from 1 kHz to 1 MHz. The radiated field of a lightning flash induces a current in the loops. The voltage signal measured in the loops is related to the flash's generated magnetic field strength by the cosine of the angle between the loop antenna and the direction to the flash. By comparing the voltage signals from the two loops, a direction to the flash can be determined. The flat plate antenna is used to resolve the 180 degree ambiguity associated with the calculations.

The direction finder can discriminate cloud-to-ground flash from other forms of lightning or noise by the electromagnetic signature. When the stepped leader reaches the ground, the return stroke is triggered producing a sharp voltage rise. This telling factor distinguishes a cloud-to-ground flash from other electromagnetic noise.

The direction finder sends the data of each registered lightning flash to the position analyzer (PA). The position analyzer triangulates data from direction finders to locate the position of a lightning flash. If the flash is in line with or directly between two direction finders (called the baseline), the position analyzer uses the ratio of the signal strengths as well.

From the position analyzer, users can view a map of the lightning data on a remote display processor (RDP). The display can focus on desired time and location windows covered by the detection network, and can show up to 30,000 flashes.

## CURRENT MODELS TO PREDICT LIGHTNING

Several attempts have been made to make models to predict both lightning occurrence and frequency. These are summarized in this section. The reader should note that of the four models presented, only one is based upon lightning detection technology. The other models were based primarily on indirect, less reliable, techniques (such as a weather observer hearing thunder or seeing lightning) and should be regarded with caution.

### Sly - 1965

In the sixties, Sly developed a set of convective indices useful in forecasting various convective processes over Alberta (Sly 1966). A modification of the Jefferson index of instability, Sly's indices took the form

$$C = C_1 = 1.6\theta_{w12m} - T_{500_{\text{mb}}} - 11$$

$$C = C_2 = 1.6\theta_{w21m} - T_{500_{\text{mb}}} - 11$$

$$C = C_1 = C_2 = m_{\text{mb}}$$

where  $\theta_{w12m}$  is the wet-bulb potential temperature ( $^{\circ}\text{C}$ ) calculated using the 1200 UTC dew point temperature and the maximum for the day,  $\theta_{w21m}$  is the wet-bulb temperature ( $^{\circ}\text{C}$ ) calculated using the 2100 UTC dew point temperature and the maximum for the day,  $T_{500_{\text{mb}}}$  is the 500 millibar

temperature ( $^{\circ}\text{C}$ ) at 00 UTC the following day, and  $m_{00}$  is a correction due to mid-level at 0000 UTC the following day.

Of the three indices, Sly found a good relationship between the second index,  $C_2$ , and lightning incidence over the Grande Prairie forest in Northwestern Alberta (Sly 1965). The values of the  $C_2$  index for days when lightning was reported by a look-out tower were compared with values for days with no lightning. Sly found that a  $C_2$  value of 31.0 was a good discriminator. Of the 106 days with a  $C_2$  below 31.0, only 9 had lightning. For  $C_2$  values above 31.0, the probability of lightning jumped to 80%, while for values above 34.0, the probability was 93%.

Although Sly's indices have merits, they are longer in use. Because of its age, Sly's research is based upon surface observation. It lacks the technological support (radar, lightning detection systems) that is so essential to severe weather forecasting today.

### **Fuquay - 1980**

As part of the National Fire-Danger Rating System (NFDRS) for the United States, Fuquay developed a scheme to describe and forecast Lightning Activity Levels (LAL), a predictor of lightning-caused forest fires.

In his model, there are 6 LALs ranging from no thunderstorms (LAL 1) to numerous thunderstorms and heavy precipitation (LAL 5). Lightning Activity Level 6 is reserved for high level thunderstorms. These are of particular interest to the forester because they are often accompanied by little to no rain.

The Lightning Activity Level is primarily a descriptive scheme that can be used by observers and forecasters. It is based on maximum cloud development, maximum height of radar echoes, radar echoes (intensity and area coverage), precipitation (amount and area coverage), and cloud to ground lightning flash rates and density. If the forecaster can predict one of these factors, he or she can then determine the LAL for the day.

### **Andersson *et al.* - 1989**

Andersson *et al.* compared the performance of three thermodynamic indices - the energy index (EI), the George's K and a modified K index (KO) - against thunder observations at weather stations in Sweden. Skill scores showed that, to a degree, all three indices were good predictors with detection rates approaching 100%. These results were hindered by high false alarm rates, as much as 40%.

The study then went on to predict lightning frequency. A regression equation to predict thunderstorm activity was built using a stepwise regression on the three indices. The regression was able to explain 37% of the variance.

The weakness of this approach was that the researchers used the thunderstorm index,  $TH$  ( $100 \times$  number of thunderstorm observations/number of observations), which is not a good measure of the lightning activity. While useful in determining the probability of lightning occurrence, the estimate of lightning frequency is categorical (low, medium, high) at best.

### Anderson - 1991

In 1991, Anderson built 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.

Anderson studied LLP lightning detection data and compared the lightning occurrence and lightning frequency in the vicinity of Stony Plain with upper air soundings from that station. The data was analyzed using a variety of statistical tests. These included  $t$ -tests and logistic regression to examine the probability of lightning occurrence, and linear and multiple linear regression to study lightning frequency.

The first approach was to predict days with lightning. To do this,  $t$  tests and stepwise logistic regressions were conducted. The  $t$  tests showed convective parameters, such as convective indices, temperatures, and moisture as the most significant in distinguishing between days with lightning and days without lightning. The results of the logistic regression models show that the potential for the predictability of lightning occurrence (the detection rate) is above 80%, though high false alarm rates, 30% on average, reduce the value of these predictions.

Parameter	Symbol	Contribution
Surface		
Fronts		LR
Moisture adx		Instability
Dry line		Instability
Thermal ridge		Instability
Convergence		LR
Instability line		Instability
880 mb		
Axle of stronger wind		LR
Low level jet		LR
Moisture adx		Instability
Dry line		Instability
Thermal ridge		Instability
Convergence		LR
700 mb		
Axle of stronger wind		LR
Dry prod		Instability
No change line		Instability
Diluent zones		LR
600 mb		
Axle of stronger wind		LR
Wind maximum		LR
Thermal trough		Instability
PVA		LR
Diluent zones		LR
250 mb		
Axle of stronger wind		LR
Wind maximum		LR
Diluent zones		LR
850-600 mb thickness ridge		LR

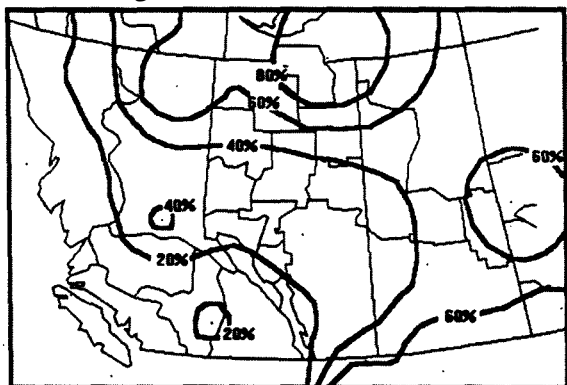
Figure 10. Severe Weather Symbols.

To predict lightning flash frequency, linear regression techniques were used. Regressions using individual variables showed a large degree of scatter ( $r$ ) but the significance of the correlation coefficient ( $P$ ) indicate that most are not due to chance. Three multiple linear regression models were built to predict lightning frequency using stepwise linear regressions. These models show that convective indices are the most important parameters to use, but with the best  $r$  squared values between 0.16 to 0.49, they do not sufficiently explain the variation.

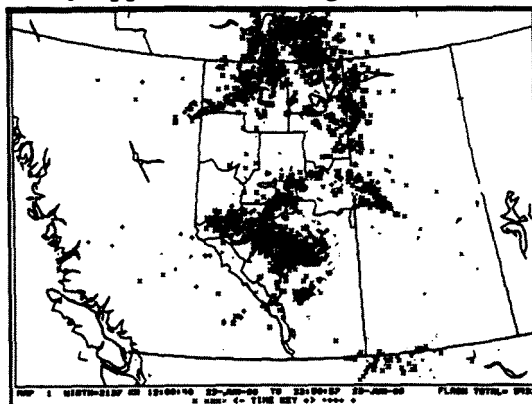
It was then shown that, from the regression equations derived through the statistical study, spatial predictions of lightning occurrence and frequency could be produced.

To account for spatial features that cannot be drawn from upper air soundings, severe weather composite maps were studied (Figure 10). These maps show parameters from various levels in the atmosphere likely to cause severe weather. This study reinforces the importance of convective parameters shown as low level moisture, surface warming,

and instability. Surface fronts, low level convergence, and positive vorticity advection (PVA) were recognized as fields that could not be accounted for by upper air soundings.

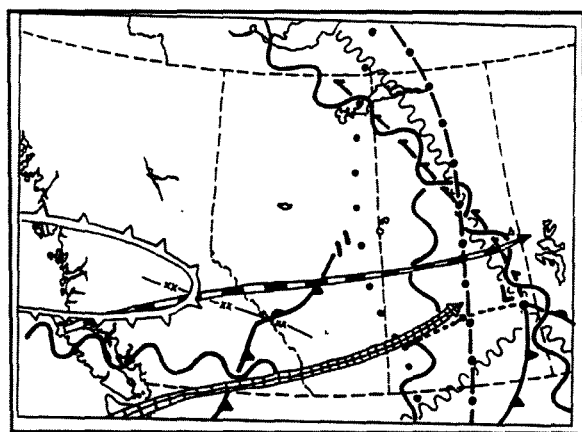


**Figure 11.** 0000 UTC June 24, 1988 negative lightning occurrence prediction map.



**Figure 12.** Lightning detection map for June 23, 1988.

Finally, a case study was presented comparing maps of forecasted negative lightning flash occurrences (Figure 11) with the actual detected lightning activity (Figure 13). The forecast maps produced acceptable results but had some short-comings because they could not assess the synoptic situation. This is clearly shown in the figures. Although the lightning activity over northern Alberta was accurately forecasted by the model, the storm over central Alberta was missed (30% probability). This storm was caused primarily by spatial features (Figure 12), namely the presence of surface fronts and convergence and the influx of positive vorticity advection (PVA). If the important spatial features from the composite map study are considered, the forecaster can adjust these maps and produce a very reliable lightning occurrence forecast.



**Figure 13.** Composite map for 0000 UTC June 24, 1988.

The conclusions Anderson state is that the intensity of convection is the most important process in lightning occurrence and frequency, and that lightning occurrence can be forecasted with reliability. A more significant message, though, is that the techniques generated were not sufficient to predict lightning frequencies reliably. Lightning frequency is a variable that had evaded most research on the subject and it comes as no surprise in his thesis that it continues to be evasive.

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# **PREDICTING THE DAILY OCCURRENCE OF PEOPLE-CAUSED FOREST FIRES <sup>1 2</sup>**

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**Information Report PI-X-103  
Petawawa National Forestry Institute  
Forestry Canada  
1991**

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<sup>1</sup>A paper presented at the Eighth Central Region Fire Weather Committee Scientific and Technical Seminar, April 3, 1992, Winnipeg, Manitoba.

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## ABSTRACT

People are responsible for starting two out of every three forest fires in Canada. To efficiently suppress these fires while they are still small, a modern forest fire control organization must be able to predict their numbers and locations one day in advance. Contrary to popular belief, these fires do not occur at random times or in random locations. Instead, experience has shown that these fires are started under specific fuel and weather conditions and that the fires are predictable. During the past 20 years, various prediction methods have been developed and tested. The procedure presented here represents the current state of one of the paths taken in the search for a more accurate prediction system.

The goal is to predict the number and location of people-caused fires that will occur the next day in a large forest region. The procedure, encoded into a computer program, uses databases containing the region's historical fire occurrence patterns and tomorrow's predicted weather and fuel moisture index values. The program is written in Fortran and runs on a Digital VAX computer; the execution time is approximately 5 CPU seconds on a VAX 750. The program produces both tabular and map output.

The program was originally developed for use at the Société de Conservation de l'Outaouais' fire center in Maniwaki in southwestern Quebec. After several fire seasons of testing in this region, it was installed in other regions of the province. During the 1989 fire season, it was extensively tested and evaluated.

## RÉSUMÉ

Au Canada, deux incendies de forêts sur trois sont causés par négligence. Pour que tels incendies puissent être éteints de façon efficace tandis qu'ils sont encore petits, il importe que l'on soit capable d'en prédire le nombre et le lieu un jour à l'avance. On croirait que ces feux peuvent survenir n'importe où et n'importe quand. Cependant, l'expérience a démontré que non seulement les feux étaient nés dans des conditions spécifiques quant à la combustion et la météorologie, mais aussi qu'il était possible de les prédire. Pendant les vingt dernières années, on a élaboré et soumis aux essais de diverses méthodes de prédiction. Le procédé dans ce rapport décrit l'étape actuelle sur une des voies de recherches que l'on suivait en vue d'un système de prédiction plus en plus précis.

Le but est de prédire d'un jour à l'avance le nombre et l'endroit des feux dans une région forestière étendue. La méthode fonctionne en tant qu'un programme d'ordinateur utilisant des bases de données. Dans ces dernières sont incorporés les détails sur les feux antérieurs, les prévisions météorologiques et l'indice de teneur en eau des combustibles. Le programme a été écrit en Fortran et il fonctionne à un ordinateur digital VAX. La durée d'exécution est environ de 5 seconds d'unité centrale au VAX 750. Les résultats peuvent être affichés en formes de tableaux ou sur cartes.

Ce programme a été réalisé d'abord au centre de prévention des incendies de Maniwaki, dans le cadre de la Société de la Conservation de l'Outaouais dans le sud-ouest du Québec, et soumis aux essais avant de l'appliquer aux autres régions de la province. Pendant la saison des incendies de 1989, on a réévalué cette méthode de façon exhaustive.

## The Fire Prediction Problem

In Canada, people's activities and machinery are responsible for igniting about two out of every three forest fires that occur during an average fire season (Ramsey and Higgins 1986; Table 1). The proportion of people-caused fires varies from province to province, ranging from 46% to 82%. The percentage of the total area burned by these fires is even more variable, ranging from 13 to 83% across Canada and averaging 17%.

Table 1. People-caused fire occurrence and area burned, 1973-1982

Region	Percentage of Total Fire Occurrence	Percentage of Total Area Burned
Canada	61	11
All Provinces	62	17
Territories	37	1
British Columbia	57	28
Alberta	53	15
Saskatchewan	46	13
Manitoba	59	28
Ontario	63	19
Quebec	82	59
Newfoundland	58	15
New Brunswick	80	83
Nova Scotia	80	43
Prince Edward Island	70	71

Note: Statistics derived from Ramsey and Higgins (1986).

To efficiently suppress these fires while they are still small, a modern forest fire control organization must be able to predict their numbers and locations one day in advance. This is needed to plan adequate aerial detection patrols and to position suitable initial attack resources in anticipation of the occurrence of these fires. Contrary to popular belief, these fires do not occur at purely random times or in random locations. Instead, experience has shown that these fires are started under rather specific conditions and that their numbers are predictable at least in probability terms.

During the past 20 years, various prediction methods have been developed and tested. A subjective scheme that requires daily input by a knowledgeable person was developed and tested by Cunningham and Martell (1974). Primitive correlation methods that relate fuel moisture indexes to average fire occurrence have existed for the past 50 years and are attached in one form or another to both the Forestry Canada and USDA Forest Service fire index systems (Gisborne 1936, Beall 1939, Van Wagner 1970, 1987, Rothermel 1972, Stocks 1983). Another approach to the forecast problem uses more sophisticated correlation methods that account for historical and current patterns with respect to weather, fuel moisture, and geographic location (Kourtz 1977). This approach

has been developed during the past 15 years and its current state is presented in this report.

Finally, the most recent approaches to fire prediction involve looking at the specific causes of people-caused fires. Here again, there are two approaches. Martell et al. (1987) use logistic regression to correlate occurrences to specific causes within a small forest region, whereas Kourtz (1989) uses expert system technology to consider various people-created risk situations and the likelihood of resulting fires.

Field tests involving these methods indicate that our knowledge of the prediction problem is slowly evolving. The following points summarize the knowledge that has been gained:

- The number of people-caused fires that will occur the next day is predictable in probability terms, with accuracy levels being adequate for most daily planning tasks.
- The Fine Fuel Moisture Code (FFMC), a component of the Canadian Fire Weather Index System, is a good indicator of the potential occurrence of people-caused fires (Van Wagner 1970). The FFMC reflects the fuel moisture conditions of the litter and fine fuels. As the fuel moisture in these fuels decreases, ignition becomes easier. This association is reflected by an increase in the occurrence of people-caused fires, especially under the influence of high winds.
- The number of fire starts in a specific geographic area is related to the number of people using that area and factors that affect the ease of ignition, such as fuel type, fuel moisture state, and wind speed.
- Historical fire occurrence data for a specific geographic area combined with the corresponding moisture content of fine fuels for the area can be used to predict the number of people-caused fires expected to occur on a specific day (Cunningham and Martell 1973).
- The occurrence of people-caused fires is adequately described by a Poisson process (Martell 1972). For example, the probability of a specific number of fires occurring on a given day within a geographic area can be calculated using the Poisson distribution, with its parameter being the number of fires expected on that day.
- A large region (i.e., 100 000 km<sup>2</sup>) can be divided into much smaller units, such as cells, in a rectangular grid (each approximately 500 km<sup>2</sup> in size) and a prediction of fire occurrence in probability terms can be made for each of the smaller units. With this procedure, location accuracy still requires considerable improvement.
- The accuracy of the predicted number of occurrences improves as the fire frequency in a

specified geographic area increases. It is difficult to assess the value and accuracy of predictions for areas where fires rarely occur.

- The location and number of fires vary throughout the fire season, especially between spring and summer. This variation in the fire occurrence rate is related to fuel type conditions, the timing of green-up, and seasonal variations in people's use of the forest.
- The quality of historical records is poor, adding little to sophisticated statistical procedures. Fire cause, ignition time, weather conditions at the site, and fuel type and moisture conditions are often crude estimates. In some cases, about all that should be stated is that there probably was a fire.
- Patterns of people-caused fires can rapidly change over time. One must be cautious when relying on historical records as the only indicator of tomorrow's fires. Historical fire statistics should be adjusted to reflect changing forest patterns and uses over the last few years as well as within the present fire season (Kourtz 1981).
- The prediction process must be robust. It must work during all fire weather situations. Predicting expected fires during low to moderate fire weather situations is a fairly easy process. Predicting fires during high or extreme fire weather situations is a much more difficult process, but also a much more important one.
- People-caused fire occurrence predictions should include a short-term learning feature. Experience has shown that under "constant" weather conditions the average fire occurrence rate over the past few days will more accurately reflect tomorrow's expected number of fires than that predicted based on historical estimates (Kourtz 1981).
- A few experienced fire personnel can predict people-caused fires more reliably than through the use of historical fire statistical approaches. Local experts have better knowledge of the number of people currently using the forest, forecasted weather patterns and their effect on fuel moisture conditions, and other subjective assessments. Artificial intelligence expert systems could encode this human knowledge and expertise (Kourtz 1989).
- There is an intimate link between fire prediction reliability and detection activity. Fire prediction systems predict visually detectable fires. Because most areas are patrolled by aircraft, if the detection dispatcher doesn't believe that there are fires present, patrol efforts will be minimal and those fires occurring will not be reported until at least the following day. This makes the current day's forecast incorrect as well as that of the next day.
- Most fire control experts want consistently reliable fire occurrence predictions that can be incorporated into daily planning sessions. Managers do not expect exact numerical

predictions, but rather some measure to identify the severity of a fire day. General classes of occurrence and some general indication of where fires are likely to occur within their region would suffice.

### Quebec's Prediction Program

A new computer program, incorporating many of the considerations discussed above, has been developed to predict daily people-caused fire occurrence for large forest regions within the province of Quebec. The program was developed and initially tested in the Outaouais region of southwestern Quebec. The main features of the program are summarized here.

#### *Goal of the Program*

The program is to be used in the late afternoon to predict the number and location of people-caused fires that will be visually detectable the next day. Because the prediction depends upon fire weather and precipitation forecasts, a provision is made during the morning of the current prediction day to incorporate the 0800 weather station rainfall values and to revise the original prediction as required. This is necessary because weather forecasts are less than reliable, especially precipitation forecasts.

#### *The Spatial Frame*

The program is designed to predict people-caused fires over a forest region of about 100 000 km<sup>2</sup>. The region is partitioned into cells that are each 0.25° in latitude and 0.25° in longitude and have an area of about 500 km<sup>2</sup>. The Outaouais fire control agency operates 24 weather stations and for each of these stations there is a daily record of weather and fire weather indexes spanning the past 10 fire seasons. Each cell is assigned weather and fire weather index values from the most appropriate weather station, which, in many cases, is the nearest weather station. In addition, there is a 10-year record of fire occurrences for each cell. The program incorporates the historical fire occurrence and fire weather information for each cell and produces a corresponding fire prediction. The regional fire occurrence prediction is then derived from the individual cell predictions.

#### *Temporal Variation*

For most Canadian regions, there are distinct periods within a fire year that have unique fire occurrence rates. Rates vary over time because of differing intensities and types of activities carried out by forest users, differing types of ignitable fuels, and differing weather and fuel moisture conditions. Previous prediction programs partitioned the fire season into spring and summer periods. However, experience has shown that conditions during these two periods are

significantly different. In fact, a transition period can be defined. The program identifies and uses three periods in the prediction process. Factors considered in defining these periods include:

- 1) initial and final dates of historical weather records, which restrict seasonal period definitions and statistical analyses;
- 2) the size of the geographic prediction cell and the corresponding number of fires and observation-days in each class;
- 3) the date and rate of regional green-up trends of the region's ground vegetation and deciduous species; and
- 4) patterns of fire occurrence during different times of the year in relation to cultural, recreational and industrial activities.

The current Quebec program uses the following time periods: spring, May 1 to May 24 ( 24 days ); transition, May 25 to June 25 ( 32 days ); and summer, June 26 to August 31 ( 67 days ).

Table 2 presents a regional breakdown of the number of people-caused fires that occurred in Quebec in 1988 during each period as well as the two highest daily totals during each period. Distinct differences are apparent, especially when the number of fires that occurred during a period is related to the total number of days in the period. The summer period has a lower fire occurrence rate than either the spring or the transition periods in five of the six regions for which data are available for all three periods. In addition to having higher fire occurrence rates, the spring and transition periods also reveal variations from one region to another. Some regions have a higher number of spring fires, whereas others, such as the Outaouais region, have higher occurrence rates during the transition period. Also, the summer period has lower daily maximum occurrence rates compared with those experienced during the spring and transition periods. These daily maximum trends are consistent across all regions of the province. Fire distribution patterns within regions also vary over the seasonal periods. Figure 1 illustrates the number of fires by prediction cell and period for the Outaouais region of Quebec. Fluctuations and changes in the pattern of fire occurrence are evident among each of the periods.

Each of the seasonal periods has unique characteristics with respect to fire prediction. Predicting fires during the summer period is an easy process because the occurrence of people-caused fires is low and daily maximum levels are low. Consequently, fire prediction forecasts are fairly accurate. The spring period has variable regional fire occurrence levels and the highest maximum daily

totals. This period requires a dynamic approach to fire prediction as the process must respond quickly to changing fuel moisture relationships. Fire predictions are less accurate during the spring. The transition period is intermediate in terms of the degree of difficulty in predicting fires and the expected accuracy of predictions relative to the other periods.

#### *Ignition Class Definition*

The FFMC for a particular day for a particular geographic cell is a good indicator of people-caused fire occurrence rates. The FFMC is a numerical rating that directly reflects the fuel moisture conditions of the litter and fine fuels and indicates the overall ease of ignition of forest fuels. Higher FFMC values indicate lower fuel moisture conditions and are closely associated with higher fire occurrence rates. Although the FFMC/fire occurrence relationship provides "ballpark" results, experience indicates that it does not adequately cover many important situations. The accuracy of fire predictions can be improved by including other factors related to the ignition process. Earlier research has identified two important elements that affect the ignition process: the ease of ignition and the rate of spread immediately after ignition (Muraro 1977). The ease of ignition is best described by the FFMC and the Duff Moisture Code (DMC), whereas the rate of spread is best described by the DMC and the Initial Spread Index (ISI). The DMC is a numerical rating of the moisture content in upper duff layers, whereas the ISI is a numerical index that combines the FFMC and wind to reflect fire spreading rates. All three indexes (FFMC, DMC, and ISI) are components of the Canadian Fire Weather Index System.

The three fire weather indexes have been combined to form a new category called the Ignition Index. This index combines fuel moisture conditions in two different fuel layers with wind speed, and attempts to identify situations that are conducive to fire ignition. Many factors govern the ease of fire ignition. High FFMC and DMC values under high winds present ideal conditions for easy ignition and high occurrence rates can be expected when large numbers of people are using the forest. Low to moderate FFMC values combined with high DMC values and high winds also represent good conditions for easy ignition. This situation, which could be caused by light rainfall affecting only the fine fuels, would have resulted in low ignition probabilities in earlier fire prediction programs. Use of the ignition class in the current program relates the ease of fire ignition in different fuel complexes to the capability of fires to spread and become detectable.



Table 2. People-caused fire occurrence in Quebec, 1988

Region	Spring (May 1 - 24)	Transition (May 25 - June 25)	Summer (June 26 - August 31)
Total Number of People-caused Fires			
La Gaspésie	41	NA	NA
Sud du Québec	59	35	9
Québec-Mauricie	78	83	19
Côte nord	21	14	28
Saguenay/Lac St-Jean	57	24	12
Outaouais	33	108	25
Nord-ouest	76	54	40
The Two Highest Daily Number of People-caused Fires			
La Gaspésie	15 6	NA	NA
Sud du Québec	16 11	7 4	3 2
Québec-Mauricie	16 16	8 8	6 2
Côte nord	5 4	3 2	2 1
Saguenay/Lac St-Jean	15 8	4 3	3 2
Outaouais	8 5	28 11	3 2
Nord-ouest	18 16	7 5	5 3

Because weather forecasts and, therefore, corresponding indexes are often inaccurate, broad class limits for the FFMFC, DMC, and wind are used to determine the Ignition Index. Other considerations in defining these limits include seasonal variations in the indexes, historical fire occurrence patterns, and the need for significant numbers of observation days and fires within the classes for each geographic cell.

Table 3 lists the FFMFC, DMC, and wind speed classes for each seasonal period used for the Outaouais region of Quebec. The FFMFC index is divided into six classes, the DMC index into five classes, and the wind speed into four classes. Note that FFMFC class limits are highest during the spring period and decline through the transition and summer periods, reflecting significantly higher FFMFC values during the pre-green-up period because of lower relative humidities. Wind speed reveals the reverse trend. Wind speed class levels are lower in the spring because of the types of fires that occur during this period. Spring fires occur mainly in grass or dead fine fuels, which require very little wind to create adequate spreading rates for continuous combustion. On the other hand, firebrands that occur during the transition and summer periods require higher wind speeds to achieve adequate fire ignition due to the type and nature of the fuels that are susceptible to ignition during these periods. The DMC category is an oddity in that class levels do not show a definite trend or pattern during different seasons. The spring period has lower index values than the summer period, but the transition period has the highest values of the three seasonal periods. The fire occurrence prediction program uses seven ignition classes that are

determined by a cell's FFMFC, DMC, and wind speed classes (Appendix 1). Thus, for a specific day and cell, given the FFMFC, DMC, and wind speed, the ignition class can be determined.

Table 4 lists fire occurrence levels by ignition class and seasonal period for the Outaouais region of Quebec. The number of fires that occurred in the cells, the number of cell-day observations, and the corresponding means are presented for each ignition class. As the ignition class level increases, the number of fires per cell increases, whereas the number of observation day's decreases. In general, more fires occur in fewer days at higher ignition class levels.

Table 3. FFMFC, DMC, and wind speed classes used for ignition class definition

Period	FFMFC	DMC	Wind Speed (km/h)
Spring	0 - 65	0 - 7	0 - 6
	66 - 79	8 - 15	7 - 12
	80 - 84	16 - 25	13 - 18
	85 - 88	26 - 38	19+
	89 - 91	39+	
Transition	92+		
	0 - 60	0 - 14	0 - 10
	61 - 80	15 - 28	11 - 20
	81 - 83	29 - 45	21 - 30
	84 - 86	46 - 58	31+
Summer	87 - 89	59+	
	90+		
	0 - 55	0 - 11	0 - 10
	56 - 71	12 - 23	11 - 20
	72 - 80	24 - 35	21 - 35
	81 - 84	36 - 48	36+
	85 - 87	49+	
	88+		

Table 4. People-caused fire occurrence levels by for the Outaouais region, 1981-1983

Period	Ignition Level	No. of Fires	No. of Observation Days	Mean
Spring	1	14	6216	0.0023
	2	6	2018	0.0030
	3	36	2355	0.0153
	4	50	4345	0.0115
	5	66	2744	0.0241
	6	49	737	0.0665
	7	8	209	0.0383
Transition	1	7	11191	0.0006
	2	6	3130	0.0019
	3	13	2998	0.0043
	4	11	2980	0.0037
	5	32	2861	0.0112
	6	22	1557	0.0141
	7	3	115	0.0261
Summer	1	12	13506	0.0009
	2	11	6947	0.0016
	3	29	8600	0.0034
	4	41	7189	0.0057
	5	79	9776	0.0081
	6	76	5133	0.0148
	7	21	841	0.0250

#### Fire Occurrence History

The fire occurrence prediction program must consider historical fire occurrence patterns, recent fire occurrence patterns, and current fuel moisture conditions for each prediction cell. Martell (1972) showed that the Poisson distribution adequately describes forest fire occurrence given the mean number of fires expected for the current weather and fuel moisture conditions. Poisson probabilities are calculated the formula

$$f(x) = \frac{\lambda^x e^{-\lambda}}{(x)!} \quad \text{for } x = 0, 1, 2, \dots \quad [1]$$

where  $x$  is the number of fires expected to occur in the cell and  $\lambda$  is the mean number of fires for the fuel moisture and weather conditions in the cell. The mean and variance must be about equal to use the Poisson distribution. This is not always the case in historical fire occurrence data; in fact, with fire occurrence the variance can often significantly exceed the mean. One can assume that the Poisson distribution holds for a specific cell, but the parameter  $\lambda$  (mean number of fires), for a specific ignition class, is itself a random variable with a gamma distribution. The gamma distribution is described by the equation

$$f(\lambda) = \frac{\alpha^v \lambda^{v-1} e^{-\alpha \lambda}}{\Gamma(v)} \quad [2]$$

where  $\lambda$  is the mean of the distribution (and also the Poisson parameter) and  $v$  and  $\alpha$  are the two parameters that define a gamma distribution. These two parameters can be defined from the mean and variance of the data set (Mangel and Clark 1986). The

variable  $v$  is a measure of the degree to which the variance exceeds the mean and is defined by the formula

$$v = \frac{\text{mean}^2}{\text{variance} - \text{mean}} \quad [3]$$

The variable  $\alpha$  is defined by

$$\alpha = \frac{v}{\text{mean}} \quad [4]$$

Mangel and Clark (1986) point out that the integrated Poisson and gamma distributions can be restructured to take the form of a negative binomial distribution. It is interesting to note that Bruce (1963) identified this distribution as being suitable for fire prediction.

#### Incorporating New Trends in Fire Occurrence

Historical means and variances for each cell and for each ignition class could be used with Poisson, gamma, or negative binomial distributions to predict the probability of  $n$  fires occurring. However, such a scheme is heavily biased by past history. New fire occurrence patterns have likely developed. One way to combine historical and recent occurrence trends for a specific ignition class and cell is with a Bayesian revision of the gamma parameter (Mangel and Clark 1986, Cunningham and Martell 1974). The Bayesian approach provides a consistent method for identifying and incorporating new patterns in fire occurrence into the prediction process. Bayes' formula is

$$LR(H:E) = \frac{P(E:H)}{P(E:H')} \quad [5]$$

where the likelihood ratio  $LR$  is defined as the probability of the event or evidence of  $E$  given a particular hypothesis  $H$  divided by the probability of the evidence given the falsity of the evidence  $H'$  (Forsyth 1984). Therefore, if the probability distribution is already known and new evidence occurs, the likelihood of the new distribution can be computed based on the new evidence.

The Bayesian approach to incorporating the information that  $t$  new observations have contributed  $n$  new fires, given a Poisson occurrence process with a gamma distribution of  $\lambda$ , is expressed by the following equation (Mangel and Clark 1986):

$$f(\lambda | n, t) = \frac{e^{-(\alpha+t)\lambda} \lambda^{n+v-1} \alpha^{n+v}}{\Gamma(n+v)} \quad [6]$$

where  $n$  is the number of fires occurring during the period and  $t$  is the number of observation days during the period. The two parameters of the gamma distribution,  $v$  and  $\alpha$ , are easy to calculate, and the Bayesian mathematics can be integrated and simplified so that the distribution is easy to update and maintain. As observation days accumulate for a given

cell and FPMC/DMC class, revisions to the previous gamma parameters can be made according to the following Bayesian updating process:

$$\text{New } v = \text{Old } v + n \quad [7]$$

and

$$\text{New } \alpha = \text{Old } \alpha + t \quad [8]$$

The mean of the revised gamma distribution, which is the Poisson parameter or the expected number of fires, is described by the formula

$$\text{Gamma-mean} = \frac{v}{\alpha} \quad [9]$$

In any system, "learning," or the inclusion of new information to modify old information, is a subjective process. With the gamma/Bayesian process, the response to new information is controlled by the duration of the updating record as well as the extent of the deviation from the historical pattern. The process quickly "forgets" historical patterns if the revision period is long. Fire prediction experience over the past 20 years has shown that both a medium-term and a short-term revision of the historical occurrence pattern are required. Here, the medium-term revision is designed to include those changes that have occurred in the historical fire pattern during the past 4 or 5 years. The short-term revision is aimed at changes taking place during the current season.

The medium-term revision is accomplished by applying the Bayesian process, starting with the historical-based gamma parameters, and modifying them using observations from the past 4 or 5 years. The resulting mean (equation [8]) is used as the fire prediction for the cell and ignition class unless this value is modified by the short-term adjustment.

For the short-term revision, a separate set of gamma parameters is carried for each cell and ignition class but, unlike the medium-term set, they are initialized to zero at the beginning of the current fire season. For each day, from the beginning of the season to the current day, the appropriate parameter sets are updated. The adjustment for short-term trends is made simply by averaging the medium- and short-term parameters.

In summary, there are five steps in preparing a regional fire prediction system according to this scheme. The five steps are performed for each cell for each of the three periods that make up the fire season. These steps include the following:

**Step 1:** Identification of the FPMC, DMC, and wind speed classes that define the appropriate ignition classes for the region of interest. Table 3 lists the class levels for the three seasonal periods as they apply to the province of Quebec.

**Step 2:** Calculation of the mean and variance of the historical fire occurrence on a cell basis for each ignition class. The problem here is the number of observations to include in the calculation knowing that these parameters serve as the basis for the medium-term updating process. Experiments showed that for Quebec, the years 1981 to 1983 were sufficient to identify the basic relationship between past fire history and fuel ignition patterns.

**Step 3:** Calculation of the parameters for the gamma distribution. These are functions of the mean and variance of step 2 (equations [2] and [3]).

**Step 4:** Calculation of the medium-term Bayesian updating process. This is a daily process that revises the appropriate gamma distribution parameters for each ignition class and observation day according to the Bayesian updating scheme. This gives the final gamma distribution parameters that reflect the fire occurrence pattern for each cell, at least at the beginning of the current fire season. The years 1984 to 1988 were used for the medium-term Bayesian updating process.

**Step 5:** Calculation of the short-term Bayesian updating process. This involves a separate estimate of the gamma parameters for each cell and ignition class. It is revised each new day of the current prediction season and is intended to give the most recent fire occurrence patterns extra weight. The calculations are identical to those used in step 4, but the starting values and the length of the updating process are different. Here, observations from the past two years are used with zero values for the starting observation days and fire occurrences. The short time frame combined with zero values for the starting parameters allow the distributions to be more volatile and to respond quicker to new information. The resulting gamma parameters respond quickly to new trends in fire occurrence. This short-term estimate is averaged with the medium-term estimate to guarantee that recent fire trends will not be too biased by past fire history.

#### *A Look at Some Historical Data*

Appendix 2 contains data for three individual cells in the Outaouais region of Quebec. These data were produced following steps 2, 3, and 4 for each ignition index class and they show the changes in cell predictions after the gamma/Bayesian updating process. The data from cell 2408 for the spring period show the impact of the Bayesian process. The cell experienced a decreasing number of fires over the last eight years and the distribution of fires by ignition index class has changed. Over the 3-year period 1981-1983, there were 18 fires, none of which occurred in ignition index classes 1 and 2. Over the 5-year period

1984-1988, there were 12 fires, five of which occurred in ignition index classes 1 and 2. The Bayesian process, as reflected by the 1984-1988 Bayesian means, provides a better representation of this new trend in fire occurrence rates and the distribution of fires by Ignition Index class than the 1981-1988 fire means. The gamma/Bayesian process produced higher mean values in ignition classes 1 and 2 and lower means in the other ignition classes and reflects the change in the people-caused fire occurrence pattern.

Data from cell 2109 for the summer period show a similar fire occurrence pattern. There were 14 fires during the 1981-1983 period and five fires during the 1984-1988 period. The gamma/Bayesian-based means again represent more realistic approximations of the most recent fire patterns than the 8-year fire averages.

Data from cell 1609 for the transition period show the effect or impact of the gamma/Bayesian process on increasing fire occurrence trends. Over the period 1981-1983, there was only one fire; whereas over the period 1984-1988, there were seven fires, five of which occurred in class 6. The Bayesian process, as reflected by the 1984-1988 gamma/Bayesian means, provides a better representation of present fire occurrence trends than the 1981-1988 fire means.

### A Fire Prediction Forecast

Once the season and FFM, DMC, and wind speed classes have been defined and the revised gamma parameters have been determined for each cell, a daily fire prediction forecast can be made. The process consists of four steps.

#### Step 1: Determination of a cell's ignition classes.

For the cell of interest, today's Fire Weather Indexes for a station are combined with the next day's fire weather forecast for the area containing the cell to calculate tomorrow's Fire Weather Indexes. The FFM, DMC, and wind speed values in this forecast are then used to determine the Ignition Index. A minor smoothing algorithm, based on the index values of the cell of interest and the surrounding four cells, is applied to the forecast values. This smoothing process is used to handle the abrupt changes occurring in cells between adjacent weather stations when large variations in precipitation occur.

Step 2: Predicting fire occurrence for a cell. Given the season and the ignition class, the corresponding medium- and short-term Bayesian estimators are determined. However, these two means may reflect different fire occurrence trends. Cells that have experienced very recent increases in the number of fires because of changes in fire occurrence patterns over the last two years will have higher short-term means than medium-term means, whereas cells that

have experienced typical fire occurrence levels will have similar values for both medium- and short-term means. Therefore, these two Bayesian means are averaged to guarantee that the mean reflects the most recent fire occurrence pattern. This average is the forecast of people-caused fires for the cell.

Step 3: Assigning a fire occurrence probability statement to the cell. The Poisson distribution is used to calculate the probabilities of one or more fires occurring in the cell given the predicted mean  $\lambda$  (equation (1)). Probabilities are more meaningful to the user than the actual number of predicted fires. Most often, the predicted number of fires for a cell is considerably less than one.

Step 4: Predicting fire occurrence for the region. Fire control agencies want to know how many fires are expected the next day and where they will occur. The answer as to where fires can be expected to occur is provided by the cell predictions and corresponding occurrence probabilities, which provide estimates of fire problem areas. These values are classified into general occurrence/severity classes and are displayed for the user in the form of colored maps of the region. The maps clearly show the specific areas of concern in the region.

The expected number of fires for the region is generated from the individual cell predictions. Because the sum of Poisson-distributed random variables is also Poisson, with the mean equal to the sum of the individual cell values, the regional probabilities of any number of fires can be calculated. From this regional summation, the Poisson process can be used to generate a confidence statement of expected fire occurrence. For example, if six fires are predicted, there is a 90% chance that from 2 to 10 fires may occur. However, there are two problems associated with this process: the regional summation can give an incomplete picture of the total expected fire situation and the associated confidence statement has little practical use because the range is too large. Each cell's distributions are unique. Cells that have experienced similar fire occurrence patterns over the years will have very stable distributions with small variances. Cells that are experiencing a changing fire occurrence pattern will have unstable distributions with large variances and will be quite volatile in their response to new information. To handle these two problems, a process has been developed, based solely on experience, that gives regional fire managers a more realistic prediction of possible fire occurrence. This process consists of a table that uses the average regional Ignition Index and the average regional relative humidity in conjunction with the total number of regional predicted fires, as reflected by the regional

probability summations (Appendix 3a). The regional averages for the Ignition Index and relative humidity are based on only those cells predicted to have some chance of a fire. The output of the table is a "narrower window" or range of expected fire occurrence. This window provides a more practical estimate of the level of expected fire occurrence than the Poisson confidence statement. For the benefit of those managers who prefer a non-numeric description, this range is further divided into one of four classes: low, moderate, high, and extreme. This classification process is unique to each region. Appendix 3b presents the rules that were used to define the fire window and fire category classes for a specific range of regional expected fire occurrence of 3.26 to 3.75.

Table 5 provides a sample output of the prediction program. The prediction was for June 11, 1988 and covered the Outaouais region of Quebec. For the region, the model predicted an average of 4.52 fires, a Poisson range of 2 to 11 fires, an adjusted window of 4 to 8 fires, a HIGH fire situation level, and a 75% chance of having 3+ fires. There were 51 cells that had some chance of a fire; in these cells, the average Ignition Index was 6 and the average relative humidity was 40. There were actually four people-caused fires on this day. In this case, the actual fire occurrence was fairly close to the model's prediction of the expected regional fire average but, more importantly, it fell within the range of the adjusted fire window.

Table 5. Sample output of the prediction Model

People-caused Fire Prediction for June 11, 1988
Fire Weather Index values and past historical fire statistics indicate that today's expected fire average will be 4.52
The overall range of expected fire occurrence is 2 to 11 fires
There are 51 cells that have expected fire occurrence levels : The average fire ignition class level is 6 The average relative humidity level is 40
The adjusted window of fire occurrence is 4 to 8 fires The regional fire situation is classified as HIGH
The probability estimate of 1 or more fires is 98% 3 or more fires is 75%

### Evaluating the Predictions

Scoring rules were used to evaluate the performance of several previous fire occurrence prediction programs. Each day, such a rule compared the previous day's prediction with the actual occurrence and assigned a numeric reward or penalty. This value was accumulated during the fire season. The size of the reward or penalty was a function of both the difficulty of the prediction situation and the nearness of the prediction to the actual occurrence. In low occurrence situations, only a small reward was assigned for predicting close to the actual occurrence. The reward was much larger for a close prediction in

situations where many fires occurred. Likewise, if there was a large discrepancy between predicted and actual fires in difficult situations, the penalty was much larger. The scoring rule used was

$$SCORE = (m - 200)^2 - (k \times (p - a)) \quad [10]$$

where  $p$  is the predicted number of fires,  $a$  is the actual number of fires, and  $k$  and  $m$  are defined by the equations

$$m = 18.8 + 4.35a - 0.0001772a + 200^3 \quad [11]$$

and

$$k = \frac{m}{\left(\frac{(15 + 1.25a)}{2}\right)^2} \quad [12]$$

Just before each day's computer prediction was made, the most experienced decision-maker made a personal prediction of occurrence. Using the same scoring rule, this prediction was rated and the result accumulated similar to the program's prediction score. At the end of the season, the two accumulated scores showed how well the program could make predictions relative to the people experienced in predicting fire occurrence. In general, scores were quite close, indicating that the computer program was about as good at predicting fire occurrence as individuals who rely on personal experience to make such predictions.

Simple statistics have also been used to evaluate the accuracy of the predictions. The number of times that the predictions were within a specified number of fires of the actual occurrence was determined. Because fire prediction is a fairly easy task during wet periods, the analysis only considered the success of the program on days that had fire activity. This method showed that past programs predicted within two fires 70-80% of the time and within one fire about 60% of the time.

Appendix 4 presents evaluation data for a 15-day spring period for four regions in Quebec. The spring period is a particularly difficult time to predict fires as these results indicate. The predicted "windows" contained the actual number of fire occurrences on 67% of the forecast days. A close look at these data illustrates some of the difficulties associated with fire prediction. Clearly, exact numerical predictions are not possible. It is more realistic to use fairly broad non-numerical classes to describe the expected occurrences. Terms such as "low", "moderate", "high," and "extreme" convey the occurrence situation to the fire control manager adequately for most planning tasks.

## SUMMARY

The computer program described here uses historical fire occurrence patterns correlated with weather and forest fuel moisture to provide forecasts of fire occurrence for the following day in a large forested region. A large region is partitioned into cells and separate predictions are made for each cell. Historical patterns of occurrences within each cell are assumed to follow a Poisson process, with the Poisson parameter having a gamma distribution. Revisions to the two gamma parameters are made by means of a Bayesian updating process that incorporates new fire occurrence deviations from the historical patterns.

The cellular fire predictions are accumulated for the regional prediction forecast. The regional forecast is modified using a subjective rule set to define a narrower range of expected fire occurrence and is then classified into one of four general fire situation categories. The end result is an operationally useful daily forecast of expected people-caused fire occurrence on a cell and regional basis.

Previous discussions have outlined the limitations of the historical correlation approach to fire prediction. There are always several important fire days within a fire season when such prediction systems fail. Although logical explanations can always be made for these failures, fire experts who utilize local knowledge of individual fire risks seem to be able to provide more consistent predictions, especially during more difficult periods. The next generation of people-caused fire occurrence prediction systems will relate estimates of the daily use of the forest and will look at specific causes. These systems will encode the expertise of the most experienced people and will incorporate historical fire statistics, expert perceptions of forest-use patterns, daily risk factors associated with each cause, levels of detection efficiency, precipitation patterns, and weather forecasts (Kourtz 1989). The program described here is intended to provide an interim solution until better programs are developed.

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## Appendix 1. Ignition class definitions

Ignition Class 1 - defined by 5 possible cases		
FFMC Class 1	DMC Class 1	Wind Class 1 or 2
	DMC Class 2	Wind Class 1 or 2
FFMC Class 2	DMC Class 1	Wind Class 1
Ignition Class 2 - defined by 8 possible cases		
FFMC Class 1	DMC Class 1	Wind Class 3 or 4
	DMC Class 2	Wind Class 3 or 4
	DMC Class 3	Wind Class 1
FFMC Class 2	DMC Class 1	Wind Class 2
	DMC Class 2	Wind Class 1
FFMC Class 3	DMC Class 1	Wind Class 1
Ignition Class 3 - defined by 22 possible cases		
FFMC Class 1	DMC Class 3	Wind Class 2 or 3 or 4
	DMC Class 4	Wind Class 1 or 2 or 3
	DMC Class 5	Wind Class 1 or 2
FFMC Class 2	DMC Class 1	Wind Class 3 or 4
	DMC Class 2	Wind Class 2 or 3
	DMC Class 3	Wind Class 1 or 2
	DMC Class 4	Wind Class 1 or 2
	DMC Class 5	Wind Class 1
FFMC Class 3	DMC Class 1	Wind Class 2
	DMC Class 2	Wind Class 1
	DMC Class 3	Wind Class 1
FFMC Class 4	DMC Class 1	Wind Class 1 or 2
Ignition Class 4 - defined by 22 possible cases		
FFMC Class 1	DMC Class 4	Wind Class 4
	DMC Class 5	Wind Class 3
FFMC Class 2	DMC Class 2	Wind Class 4
	DMC Class 3	Wind Class 3 or 4
	DMC Class 4	Wind Class 3
	DMC Class 5	Wind Class 2
FFMC Class 3	DMC Class 1	Wind Class 3 or 4
	DMC Class 2	Wind Class 2 or 3
	DMC Class 3	Wind Class 2
	DMC Class 4	Wind Class 1 or 2
	DMC Class 5	Wind Class 1
FFMC Class 4	DMC Class 1	Wind Class 3
	DMC Class 2	Wind Class 1 or 2
	DMC Class 3	Wind Class 1
FFMC Class 5	DMC Class 1	Wind Class 1 or 2
FFMC Class 6	DMC Class 1	Wind Class 1
Ignition Class 5 - defined by 22 possible cases		
FFMC Class 1	DMC Class 5	Wind Class 4
FFMC Class 2	DMC Class 4	Wind Class 4
	DMC Class 5	Wind Class 3
FFMC Class 3	DMC Class 2	Wind Class 4
	DMC Class 3	Wind Class 3 or 4
	DMC Class 4	Wind Class 3
	DMC Class 5	Wind Class 2 or 3
FFMC Class 4	DMC Class 1	Wind Class 4
	DMC Class 2	Wind Class 3

Appendix 1. (Cont'd)

Ignition class 5 (cont'd)		
FFMC Class 5	DMC Class 3	Wind Class 2
	DMC Class 4	Wind Class 1 or 2
	DMC Class 5	Wind Class 1
	DMC Class 1	Wind Class 3
	DMC Class 2	Wind Class 1 or 2
FFMC Class 6	DMC Class 3	Wind Class 1
	DMC Class 4	Wind Class 1
	DMC Class 1	Wind Class 2
	DMC Class 2	Wind Class 1
Ignition Class 6 - defined by 22 possible cases		
FFMC Class 2	DMC Class 5	Wind Class 4
FFMC Class 3	DMC Class 4 or 5	Wind Class 4
FFMC Class 4	DMC Class 2	Wind Class 4
	DMC Class 3	Wind Class 3 or 4
	DMC Class 4	Wind Class 3
FFMC Class 5	DMC Class 5	Wind Class 2
	DMC Class 1	Wind Class 4
	DMC Class 2	Wind Class 3
	DMC Class 3	Wind Class 2 or 3
	DMC Class 4	Wind Class 2
FFMC Class 6	DMC Class 5	Wind Class 1 or 2
	DMC Class 1	Wind Class 3 or 4
	DMC Class 2	Wind Class 2 or 3
	DMC Class 3	Wind Class 1 or 2
	DMC Class 4	Wind Class 1
Ignition Class 7 - defined by 19 possible cases		
FFMC Class 4	DMC Class 4	Wind Class 4
FFMC Class 5	DMC Class 5	Wind Class 3 or 4
	DMC Class 2	Wind Class 4
	DMC Class 3	Wind Class 4
	DMC Class 4	Wind Class 3 or 4
	DMC Class 5	Wind Class 3 or 4
FFMC Class 6	DMC Class 2	Wind Class 4
	DMC Class 3	Wind Class 3 or 4
	DMC Class 4	Wind Class 2 or 3 or 4
	DMC Class 5	Wind Class 1 or 2 or 3 or 4

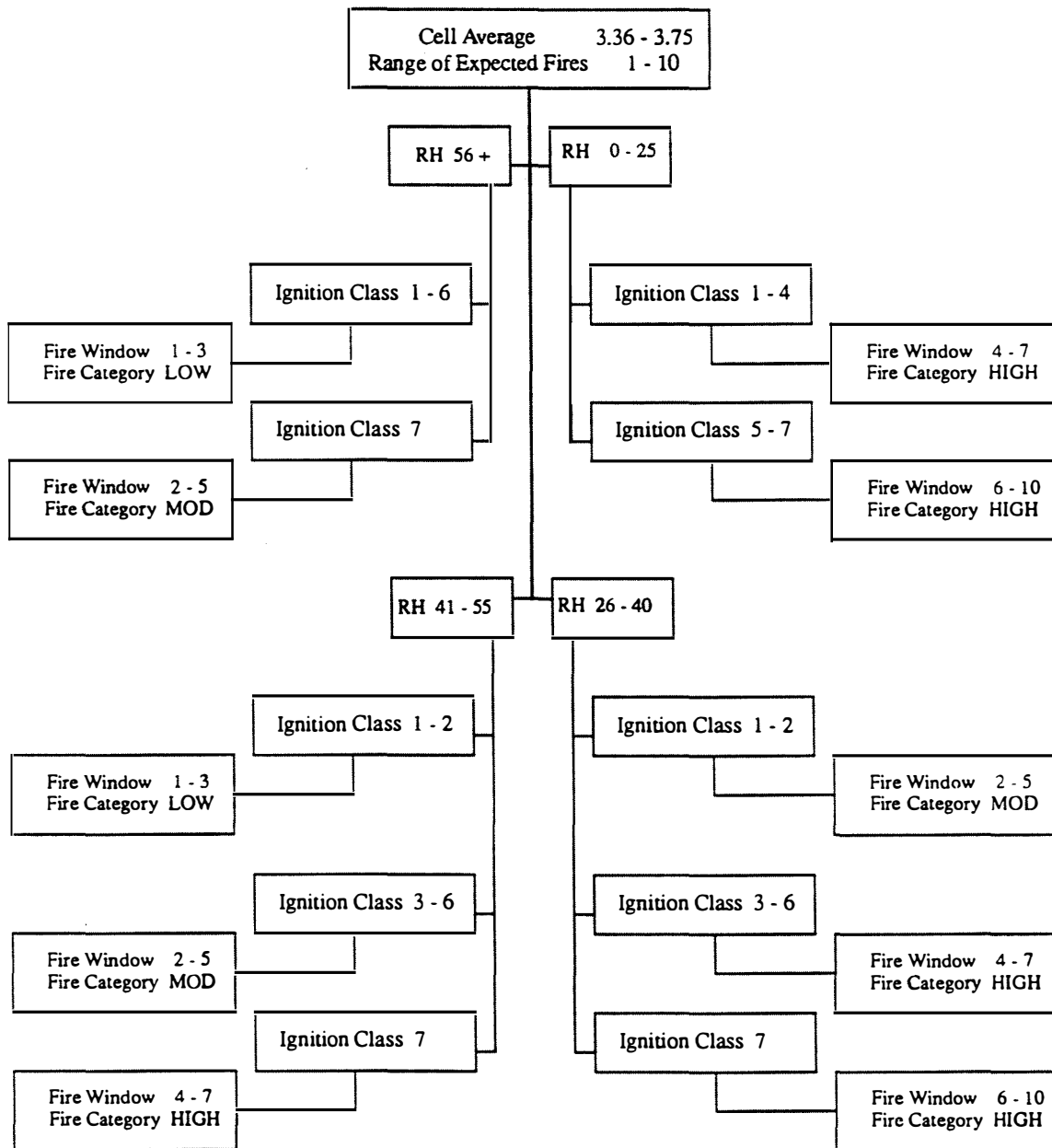
**Appendix 2. Statistical comparison of three cells in the Outaouais region of Quebec**

Ignition Level	1981-1983			1984-1988			1981-1988
	No. of Fires	No. of Days	Mean	No. of Fires	No. of Days	Bayesian Mean	Overall Mean
Cell 2408, spring period							
1	0	28	0.0000	1	35	0.0286	0.0159
2	0	7	0.0000	4	30	1.1333	0.1081
3	6	13	0.4615	2	24	0.0867	0.2162
4	4	18	0.2222	0	13	0.0060	0.1290
5	5	17	0.2941	3	19	0.1598	0.2222
6	2	10	0.2000	1	12	0.0941	0.1364
7	1	3	0.3333	1	11	0.0909	0.1429
Cell 2109, summer period							
1	1	62	0.0161	0	100	0.0001	0.0062
2	0	40	0.0000	0	40	0.0000	0.0000
3	0	38	0.0000	0	57	0.0000	0.0000
4	3	29	0.1034	2	54	0.0377	0.0602
5	3	49	0.0612	2	2	0.0280	0.0413
6	7	36	0.1944	0	70	0.0005	0.0660
7	0	14	0.0000	1	9	0.1111	0.0435
Cell 1609, transition period							
1	0	43	0.0000	0	47	0.0000	0.0000
2	0	21	0.0000	0	26	0.0000	0.0000
3	0	18	0.0000	0	21	0.0000	0.0000
4	0	19	0.0000	1	14	0.0714	0.0303
5	1	13	0.0769	0	35	0.0001	0.0208
6	0	11	0.0000	5	33	0.1515	0.1136
7	0	3	0.0000	1	16	0.0625	0.0526

**Appendix 3. Classification of expected regional fire occurrence based on the averages of expected fires, relative humidity, and ignition classes**

Regional Fire Averages	Poisson Fire Range	Adjusted Fire Windows			
		Average Relative Humidity			
		56+	41 - 55	26 - 40	0 - 25
0.00 - 0.10	0 - 1	0 - 1	0 - 1	0 - 1	0 - 1
0.11 - 0.44	0 - 2	0 - 1	0 - 1	0 - 1	0 - 2
0.45 - 0.74	0 - 3	0 - 1	0 - 1	0 - 2	1 - 3
0.75 - 1.08	0 - 4	0 - 1	0 - 2	0 - 3	1 - 4
1.09 - 1.42	0 - 5	0 - 1	0 - 2	1 - 3	2 - 5
1.43 - 1.76	0 - 6	0 - 2	0 - 3	1 - 4	2 - 6
1.77 - 2.25	0 - 7	0 - 2	0 - 3	1 - 4	3 - 7
2.26 - 2.75	0 - 8	0 - 2	1 - 3	2 - 5	3 - 8
2.76 - 3.25	1 - 9	1 - 3	2 - 5	3 - 7	4 - 9
3.26 - 3.75	1 - 10	1 - 3	2 - 5	4 - 7	6 - 10
3.76 - 4.75	2 - 11	2 - 4	3 - 5	4 - 8	7 - 11
4.76 - 5.75	2 - 12	2 - 5	4 - 7	5 - 9	8 - 12
5.76 - 6.75	3 - 14	3 - 5	4 - 8	6 - 10	9 - 14
6.76+	4 - 16	4 - 6	5 - 9	8 - 11	10 - 16

**Appendix 3 - Cont'd**  
**(b) Sample of Rule Oriented Classification Method**



Appendix 4. Comparison of model results in four regions of Quebec for the spring period of 1988

Date	Regional Cell Averages for			Expected Fires			Actual No. of Fires	
	Relative Humidity	Ignition	Prediction	Range	Window	Category		
Québec - Mauricie Region								
May	1	75	1	0.41	0-2	0-1	Low	0
	2	59	1	0.53	0-3	0-1	Low	0
	3	27	4	2.92	1-9	3-7	Moderate	1
	4	22	4	3.71	2-10	4-7	High	6
	5	24	5	5.53	2-12	8-12	Extreme	9
	6	24	5	5.68	2-12	8-12	Extreme	16
	7	28	5	5.26	2-12	6-9	High	10
	8	20	5	5.38	2-12	8-12	Extreme	16
	9	31	5	4.62	2-11	4-8	High	3
	10	43	5	6.14	3-14	4-8	Moderate	2
	11	62	4	2.43	0-8	0-2	Low	0
	12	29	4	2.79	1-9	3-7	Moderate	4
	13	53	4	3.34	2-10	2-5	Moderate	1
	14	38	1	0.79	0-4	0-2	Low	4
	15	36	3	1.90	0-7	1-4	Moderate	1
Saguenay/Lac-St Jean Region								
May	1	72	1	0.50	0-2	0-1	Low	0
	2	50	1	0.50	0-3	0-1	Low	0
	3	14	5	2.98	1-9	4-9	High	1
	4	13	5	3.94	2-11	7-11	Extreme	6
	5	19	5	3.74	2-10	6-10	High	6
	6	34	5	4.24	2-11	4-8	High	3
	7	27	5	3.83	2-11	4-8	High	8
	8	16	6	7.41	4-16	10-16	Extreme	15
	9	34	6	3.55	2-10	4-7	High	5
	10	38	6	3.62	2-10	4-7	High	8
	11	57	4	1.60	0-6	0-2	Low	0
	12	29	4	2.16	0-7	1-4	Moderate	2
	13	54	5	2.74	0-8	1-3	Low	1
	14	35	2	0.66	0-3	0-2	Low	2
	15	41	4	1.25	0-5	0-1	Low	0
Outaouais Region								
May	1	62	2	1.37	0-5	0-1	Low	0
	2	56	3	1.51	0-6	0-2	Low	0
	3	31	3	2.14	0-7	1-4	Moderate	4
	4	26	4	2.39	0-8	2-4	Moderate	2
	5	28	4	2.20	0-7	1-4	Moderate	3
	6	30	4	2.60	0-8	2-5	Moderate	5
	7	31	4	2.43	0-8	2-5	Moderate	8
	8	28	5	2.96	1-9	3-7	Moderate	2
	9	43	5	3.76	2-11	3-5	Moderate	2
	10	57	5	2.46	0-8	0-2	Low	0
	11	53	3	1.36	0-5	0-1	Low	1
	12	48	3	2.35	0-8	1-3	Low	0
	13	77	1	0.97	0-4	0-1	Low	0
	14	38	1	0.71	0-3	0-2	Low	1
	15	54	2	1.35	0-5	0-1	Low	2

Appendix 4. (con'd)

		Regional Cell Averages for			Expected Fires			Actual
Date		Relative Humidity	Ignition	Prediction	Range	Window	Category	No. of Fires
Sud d'Québec Region								
May	3	NA	NA	NA				
	4							
	5	23	5	3.46	2-10	6-10	High	4
	6	32	5	4.25	2-11	4-8	High	11
	7	28	6	3.99	2-11	4-8	High	4
	8	39	5	3.88	2-11	4-8	High	8
	9	27	6	4.51	2-11	4-8	High	6
	10	46	6	4.20	2-11	3-5	Moderate	2
	11	66	4	1.95	0-7	0-2	Low	0
	12	38	4	2.50	0-8	2-5	Moderate	0
	13	29	6	5.04	2-12	6-9	High	16
	14	56	2	0.88	0-4	0-1	Low	1
	15	41	4	1.31	0-5	0-1	Low	1

# Predicting the Daily Occurrence of Lightning-Caused Forest Fires<sup>1 2</sup>

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Information Report PI-X-112  
Petawawa National Forestry Institute  
Forestry Canada

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<sup>1</sup>A paper presented at the Eighth Central Region Fire Weather Committee Scientific and Technical Seminar, April 3, 1992, Winnipeg, Manitoba.

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## Abstract

Lightning causes one third of the 9000 wildfires that occur in Canada. Annually, these lightning-caused fires account for 90% of the area burned and cost Canadians at least 150 million dollars in suppression costs and values destroyed. Unlike the fires caused by human negligence, lightning-caused fires often occur in multiple numbers in remote locations. A modern fire control organization can suppress all of these fires while they are still small only if it has time to position sufficient suppression forces before the fires occur. Therefore, predicting the occurrence of lightning fires hours in advance is an essential component of a successful suppression strategy.

This paper describes the method currently used to predict the daily number and location of lightning-caused fires. A network of automated lightning sensors provides the locations and numbers of cloud-to-ground lightning flashes. For each flash the appropriate weather, fuel type, and moisture data are combined with models of the ignition, smouldering, and detectability processes. The ignition model predicts the chance of a flash causing ignition. The detectability model forecasts the probability of a fire being visually detectable during the burning period. The smouldering model tells us the chances of a fire surviving overnight (usually in a smouldering state).

Because fires can remain in a dormant state for long periods, each flash that occurred during the previous 10 days is considered a potential ignition point for the current day. Fires predicted to have been ignited up to 10 days earlier are given the opportunity to smoulder; they are removed from consideration after detection. Remaining fires combined with likely new fires and the expected number of detectable fires during the next burning period gives the number of fires predicted for that day.

Evaluation results are presented and discussed. In general, the prediction program produces fair to good results for small to medium morning storms and medium to large overnight storms. As well, for the previous day, the smouldering/survival model seems to work well. Poor predictions are generated, however, from afternoon storms, from occasions when rainfall data is not available, and from the smouldering model for periods longer than two days.

The prediction program is perhaps best thought of as being an expert system where specific knowledge of lightning physics, rainfall patterns, and fire behavior are combined with expert opinions of the various lightning fire occurrence processes. There is still much to learn about lightning physics, how fires are ignited, the conditions necessary for ignition, the smouldering process, and the conditions needed for smoke production.

## Résumé

La foudre cause le tiers des 9 000 incendies de forêt qui se déclarent au Canada. Chaque année, les incendies de cette origine consomment 90 % de la superficie totale brûlée par les incendies et ils coûtent aux Canadiens au moins 150 millions de dollars en biens détruits et en opérations d'extinction. Contrairement aux incendies causés par la négligence humaine, les incendies allumés par la foudre surviennent souvent en nombre élevé dans des localités éloignées. Cependant, un organisme moderne de lutte est en mesure d'éteindre tous ces feux lorsqu'ils sont encore de modestes foyers, mais seulement au cas où il disposerait de suffisamment de temps pour déployer les équipes d'intervention avant que le feu ne se propage. Pour qu'une telle stratégie porte fruit, il faut donc prédire, des heures d'avance, la survenue des incendies dus à la foudre.

L'article décrit la méthode dont on se sert pour prédire le nombre et l'emplacement quotidiens des incendies causés par la foudre. Un réseau de capteurs automatisés saisit l'emplacement et le nombre d'éclairs au sol. Pour chaque éclair, on utilise les données convenables sur le type de combustibles, la météo et l'humidité dans des modèles des processus d'allumage, de combustion lente et de détectabilité. Le modèle d'allumage prédit la probabilité qu'un éclair allume un foyer de combustion. Le modèle de détectabilité prédit la probabilité que le foyer soit visible durant les heures dangereuses (pour l'incendie). Enfin, le modèle de combustion lente renseigne sur la probabilité qu'un feu se maintienne jusqu'au lendemain, habituellement en couvant.

Comme les feux peuvent couvrir pendant longtemps, chaque éclair observé au cours des dix journées qui ont précédé est considéré comme un foyer potentiel pour le lendemain. Les feux qui auraient été allumés jusqu'au dixième jour précédent sont considérés comme ayant eu la possibilité de couvrir; ils cessent d'être pris en considération dès qu'ils sont détectés. Aux feux résiduels, on ajoute les nouveaux feux susceptibles de se déclarer et le nombre prévu de feux détectables au cours de la prochaine période dangereuse pour obtenir le nombre de feux prédits pour la journée où on se trouve.

Les résultats des évaluations sont présentés et expliqués. En général, le programme de prédiction donne des résultats assez bons pour les orages petits à moyens qui surviennent en matinée ainsi que pour les orages moyens à gros de nuit. De même, pour la veille, le modèle de combustion lente et de survie des feux semble fidèle. Toutefois, les prévisions laissent à désirer quand il s'agit des orages d'après-midi, des précipitations dont on ne connaît pas la quantité et du modèle de combustion lente appliqué à des périodes de plus de deux jours.

Le programme de prédiction pourrait être considéré davantage comme un système expert: les connaissances précises de la physique de la foudre, de la répartition géographique des précipitations et du comportement du feu sont combinées à l'opinion des spécialistes sur les divers processus par lesquels se déclarent les incendies dus à la foudre. Il reste beaucoup à apprendre sur la physique de la foudre, les modalités d'allumage, les conditions nécessaires à l'allumage, le processus de combustion lente et les conditions nécessaires à la production de fumée.

## The Lightning-caused Fire Problem

Lightning-caused fires represent a major concern to Canadian forest fire control agencies. Between 1973 and 1982, lightning was responsible for starting 34% of all forest fires or approximately 3100 annually. Although only one out of every three was caused by lightning, these fires destroyed an annual average of 1.8 million hectares or 87% of the total area burned (Ramsey and Higgins 1986). Although specific statistics on annual fire control expenditures and the dollar value of losses are not available, estimates suggest that lightning-caused fires use up three quarters of the Canadian fire suppression budget of \$109 million. Similarly, the dollar value of losses resulting from these fires has been conservatively estimated to be about equal to the suppression costs.

The high suppression costs and losses associated with lightning-caused fires are related to their remote locations and multiple occurrence patterns. Localized thunderstorm cells drift across remote forest regions igniting a variable number of fires depending upon fuel type and fuel moisture conditions. Large storms with thousands of cloud-to-ground lightning flashes may not start any fires, whereas small storms with only a few flashes may start a fire with almost every flash. Typically, in the Canadian boreal forest, an active storm cell producing little or no rain over dry forest fuels will result in dozens of fires in close proximity to each other. Sequences of such cells can result in hundreds of lightning-caused fires in a forest region in a single day. The large number of simultaneous occurrences combined with their often remote location make detection and attack difficult. Failure in either detection or initial attack can lead to the development of large fires under optimal burning conditions. The positioning of sufficient detection and initial attack resources in anticipation of expected lightning-caused fires is a necessary component of small-fire suppression philosophy. A good lightning-caused fire prediction system coupled with a modern visual/infrared detection system and strong air attack capability has the potential to eliminate large lightning-caused forest fires.

The prediction system described in this paper relies heavily on published knowledge of lightning physics, laboratory experiments investigating ignition and smoldering processes

using forest fuels and lightning simulators, lightning sensor networks, and weather and fuel database information. Most of all, it relies on some 20 years of experience in trying to predict lightning-caused fires. As such, there are many subjective opinions as to the various processes that are important and many assumptions made about the nature of these processes. In effect, this lightning-caused fire prediction system is a large expert system.

## General Structure of the Prediction System

The lightning-caused fire prediction system described here attempts to provide the detection and initial attack components of a fire control organization with adequate warning of the location and number of lightning-caused fires that are likely to occur during the current or next burning period. To accomplish this, the system combines real-time lightning occurrence information from provincial lightning sensor networks with forest fuel type, fire weather, and fire behaviour information. A large region, say 100 000 km<sup>2</sup>, is partitioned into rectangular geographic units or cells approximately 50 km<sup>2</sup> in size. In a modern fire management system, these cells constitute the basic structure for fire, weather, and fuel information. Data on lightning flashes, detected by sensors; fuel types, usually estimated from satellite images; and precipitation rates, currently derived from the closest weather station but in the near future from precipitation radar, are stored for each of these cells. A lightning-caused fire prediction is made for each cell and these, in turn, are accumulated to make regional fire predictions. This system was originally developed for and tested at the fire control center of the Société de Conservation de l'Outaouais located in southwestern Quebec. The system is now being implemented in other forest fire regions of the province.

The lightning-caused fire prediction process has four components (Figure 1). The first component in the process involves gathering information on the number of cloud-to-ground lightning flashes, their occurrence times, and types (positive or negative) for each 50 km<sup>2</sup> cell. This information is supplied through links to a fully computerized lightning location system.

The second component predicts the number of lightning-caused firebrands that can be expected.

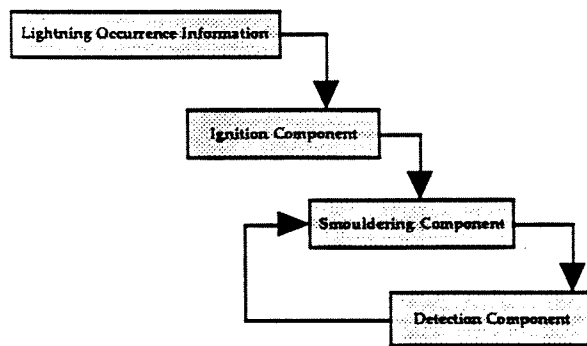


Figure 1. Components of the lightning-caused fire process.

Because, on average, relatively few lightning flashes cause forest fires, lightning occurrence information must be combined with fuel type, fuel moisture, fire weather, and fire behavior information to estimate the number of firebrands that can be expected from lightning activity.

The third component predicts, firstly, the chance of a firebrand becoming a smoldering fire and, secondly, the chance that this smoldering fire can survive, if necessary, from one day's burning period to the next.

The fourth component in the process estimates the number of smoldering fires that will become visually detectable during the forecast burning period. This estimate constitutes the final lightning-caused fire prediction. Smoldering fires that do not become detectable in the forecast burning period have the potential to smolder to the next burning period. Such fires are called "holdover" fires. It is suspected that these fires can survive up to 10 days. Their survival from one burning period to the next depends on when they were ignited, the characteristics of the fuel in which they are smoldering, and current weather and fuel moisture conditions.

## Lightning Occurrence Information

### *The Nature of Lightning Flashes*

A basic understanding of the physics of lightning is necessary to predict the occurrence of lightning-caused fires. Lightning is defined as the rapid and massive discharge of atmospheric electricity from clouds during a thunderstorm. The first remote measurement of thunderstorm electrical fields was conducted by Wilson (1916), who researched the physics of lightning and was the first to describe the

electrical structure of thunderstorms. Subsequent research has greatly expanded our knowledge of lightning and in the process has identified four basic types of lightning discharges: cloud-to-cloud, cloud-to-air, intercloud, and cloud-to-ground (Uman and Krider 1989). Cloud-to-ground lightning has been studied extensively because of its destructive nature.

Every cloud-to-ground flash can be categorized as being either negative or positive. During a typical large eastern Canadian storm, about 5 000 cloud-to-ground flashes might occur during an 8 h period. Approximately 90% of these flashes are negative, i.e., areas of a cloud containing an excessive negative charge, usually located at the base of the cloud, originate a discharge to the ground. Within a lightning path, a negative flash can have one or more rapid discharge pulses (return strokes) occurring faster than the eye can follow. Each return stroke has a rapid and massive discharge phase, which might be followed by a low-current phase during which a relative trickle of current continues for a much longer period of time. Between 25 and 50% of all cloud-to-ground flashes have this continuing current component (Uman and Krider 1989). These continuing currents are very powerful, on the order of 30 to 200 A (Shindo and Uman 1989). Latham (1980) constructed a model that predicted the core temperature of these continuous currents to be between 6 000 and 12 000°K. Orville (1972) recorded even higher amperages and temperatures in isolated severe flashes.

Unlike negative flashes, almost all positive flashes have continuous current components (Latham 1989) and usually have a single return stroke lasting at least 61 ms (Fuquay 1980).

Flashes with continuous current components are of interest because they have the capability of starting forest fires (Bellaschi 1947; Fuquay et al. 1967, 1979). Flashes with return strokes in excess of 40 ms are referred to as long continuous currents (Kitagawa et al. 1962; Fuquay 1980; Shindo and Uman 1989). Previous research indicates that, on average, over a fire season approximately 20% of all negative flashes have a long continuous current component (Fuquay 1980). However, recent work has identified two other types of continuous current flashes: short continuous currents, which last from 10 to 40 ms, and "questionable" continuous currents, which

last from 1 to 10 ms (Shindo and Uman 1989). The percentage of continuous current flashes occurring during a storm that have the potential to start forest fires varies from 12 to 50%.

The fire-starting mechanisms of lightning are still unknown. It is speculated that lightning strikes a forest target because it is, at least initially, a good electrical conductor due to moisture on its surface or moisture within its structure. A short-duration return stroke has plenty of energy but exists for too short a time to completely evaporate the conducting channel. At most, the target may be blown apart by the pressure of superheated steam. A flash with a continuous current component, on the other hand, has the necessary time, during the long current flow period, to evaporate the moisture in the conducting path, thereby creating electrical resistive heating sufficient to char or ignite the target.

#### *Capturing Lightning Occurrence Information*

At present, Canadian forest fire control Agencies use Lightning Location Protection Incorporated's lightning sensor system (Noggle et al. 1976) to capture lightning information as each flash occurs. This system consists of a set of direction-finding sensors and a central position analyzer. Each sensor can "see" many of the flashes that occur to a distance of about 150 km depending on the energy level of the flash. High-energy flashes, representing only a small proportion of the total number, can be seen to distances of 300 to 400 km. Low-energy flashes, on the other hand, can be missed even when they occur close to the sensor. Direction finders have internal algorithms that differentiate cloud-to-ground flashes from all other types of flashes. For each cloud-to-ground flash, the direction finders determine and record the direction, time, polarity, strength, and number of return strokes. This information is transferred by computer to the central position analyzer where a triangulation procedure estimates the flash's position. The lightning location information and the corresponding times are stored as a table, the information from which can be displayed as points on a map, and as individual cell summaries showing flash characteristics by frequency and time classes. This real-time capture and storage of lightning flash data is the first step in the lightning prediction process.

## **Lightning Ignition Component**

### *Quality of the Information*

The ignition of forest fuel by a lightning flash depends on many factors. Some necessary conditions must be met for a lightning-caused fire to occur. The lightning flash must have a continuous current component of sufficient duration. Somewhere along the current's path there must be combustible fuel. This fuel must have the necessary bulk density and moisture conditions to support ignition. Precipitation on the ignited fuel must be minimal to support sustained combustion or ignition must take place in a location protected from the rain.

Unfortunately, most of the information needed to predict the consequences of a specific cloud-to-ground flash is not available. The lightning detection systems that are operated over most of Canada's protected forests at present do not provide exact flash locations. Timing problems, errors associated with sensor location and orientation, and inadequate sensor pointing resolution resulting in large baseline and triangulation errors all combine to limit the accuracy of lightning flash locations. These errors increase as distance from the sensors increases. Position errors of several kilometres are common. In addition, a significant number of flashes are not even detected.

Even if the exact location of every flash were known, it would not be possible to accurately model the ignition process because other critical information, such as fuel age, bulk density, organic depth, and moisture content, is not available. At present, timber stand information for most forest regions of Canada is not location specific and is often 10 years old. Digital geographic information systems as they relate to timber stands are at least 5 years down the road for most regions of Canada. Likewise, detailed precipitation information at specific ground locations, which is critical for fuel moisture calculations, will not be available until large precipitation radar networks are established. At present, precipitation measurements are recorded only twice a day at widely scattered weather stations throughout a region. Thus, the prediction system is forced to deal with general information about lightning occurrences, fuel type and moisture conditions, and the fire environment. This is accomplished by working with information

summarized at the cell level rather than at each flash's location. Predicting the number of lightning ignitions in a specific cell requires that assumptions be made about the proportion of continuous current flashes received, the precipitation pattern, and the structure and moisture content of combustible fuels within the cell.

Several lightning ignition models have been developed in the past (Kourtz 1977, 1984; Fuquay et al. 1979). These models, which use lightning activity, storm movement, and fuel moisture and bulk density information, have been tested operationally by several fire control agencies in Canada and the United States with varying levels of success. These prediction models make many assumptions about the physical properties of storm cells and lightning flashes, precipitation patterns, and fuel types and moisture conditions. The system described in this report is similar in that it incorporates the best available sensor data, the latest research results, and expert opinion to estimate and describe the physical properties of the lightning flashes and the fire environment.

#### *Elements of the Ignition Process*

Determining lightning-caused fire ignitions requires estimating the number of continuous current flashes, precipitation characteristics, and the state of combustible fuels. Figure 2 illustrates the various components used to make these estimates.

#### (1) Estimating the Number of Continuous Current Flashes

Estimating the proportion of lightning flashes that have a continuous current component is a necessary step in predicting lightning-caused ignitions. Research has shown that 12 to 50% of all negative cloud-to-ground flashes and 95% of all positive cloud-to-ground flashes have a continuous current component. Negative continuous current flashes vary in duration from 1 ms to over 40 ms and are classified as questionable, short, and long, whereas positive continuous current flashes are in excess of 61 ms in duration. Research has shown that fires can be started by both.

Latham (1989) describes calculating the chance that a cloud-to-ground flash will have a continuous current component based on the number and duration of the return strokes.

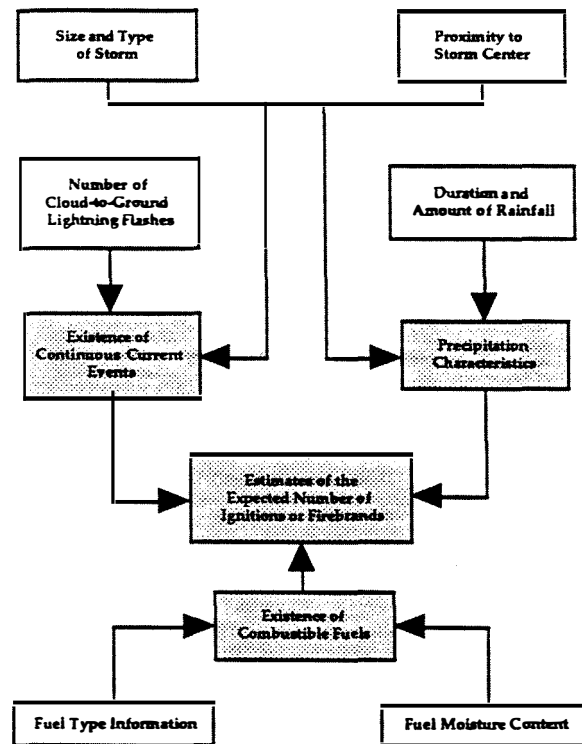


Figure 2. The lightning-caused fire ignition phase.

However, today's lightning location systems measure the polarity of each flash and the number of return strokes but not their duration. In the near future, these systems could be modified to monitor return stroke duration, making it possible to use Latham's continuous current estimation procedures. Until then, the proportion of continuous current flashes occurring during a storm must be estimated for individual storm cells.

Latitude, time of day, and seasonal variation are important factors in estimating the occurrence of continuous current events. Baughman and Schmid (1977) found that lightning storms occurring in Alaska were generally smaller, more isolated, less intense, and produced fewer continuous current flashes than storms that occurred farther south in western Montana. Also, the severity of the storms differed based upon the time of day at which they occurred. In Alaska, the most intense storms occurred late in the morning and early in the afternoon, whereas in Montana they occurred late in the afternoon. This work was substantiated by Orville (1990), who found that the characteristics of lightning flashes are sensitive to latitude. His study of lightning flashes

occurring in eastern United States revealed that the peak current of lightning flashes occurring in Florida was twice that of lightning flashes occurring in New England. Flannigan and Wotton (1991) found seasonal trends in the occurrence of lightning in northwestern Ontario. They observed that lightning activity increased in June to reach a maximum in July and then declined slightly in August and sharply in September.

Studies on the occurrence of lightning-caused fires have been conducted in Quebec, Ontario, and British Columbia. Relationships between the size and severity of storm cells, the number and location of flashes, the amount and location of precipitation, and subsequent fire occurrence rates have been studied extensively. It has been found that small, isolated, late-afternoon storms, which had a low number of flashes, were often responsible for starting a high proportion of forest fires. Conversely, large lightning storms with high concentrations of flashes near the storm's center had low associated fire occurrence rates. Higher amounts of precipitation, which occur at the center of larger storms, is one possible explanation for the apparent paradox. Another explanation is the variation in continuous current events within the storm and the capability of higher energy lightning flashes to arc out from the center of the smaller storm cells to the outside perimeters, thereby starting a fire. These studies showed that the occurrence of lightning-caused fires depends on the size and severity of lightning storms and on the proximity of the flash to the center of the storm.

The lightning-caused fire prediction process begins by estimating the proportion of continuous current lightning flashes that has occurred within each cell within the last 8 h period. The continuous current flashes are related to the size

of the storm and the proximity to the storm center. Classifying the lightning storm is the first step. The forest region is divided into 8 to 10 partitions of approximately 12 000 km<sup>2</sup>. For each partition, the total number of flashes in the partition and percentage area that received lightning activity are used to classify the storms into five categories (Table 1).

Table 1. Storm size classification

Storm type	Number of flashes	
	0-40% area coverage	41-100% area coverage
Petite	0 - 100	0 - 250
Small	101 - 250	251 - 500
Medium	251 - 600	501 - 900
Large	601 - 1200	901 - 1800
Gross	1201+	1801+

Notes: Partition size, 12 000 km<sup>2</sup>; time period, 8 h.

Once the storm is classified, an attempt is made to classify the storm's center and edges. This is done using the number of flashes in each cell and the storm classification for the partition (Table 2).

A two-digit number is used to define a cell's combined storm size and position within the storm. For example, 54 refers to the center (4) of a gross storm (5); whereas 51 refers to the outside edge (1) of a gross storm (5).

Figure 3 shows a single partition's storm activity on the night of July 31, 1988, in northwestern Ontario. There were 2995 lightning flashes in the partition and 79 of the 80 cells had some amount of lightning activity.

Once the storm size and spatial components are classified for each cell, the proportion of continuous current flashes can be estimated (Table 3). These estimations are based on several

Table 2. Cell storm position classification

Storm type	Basemap cell storm position			
	Storm center (4)	Near storm center (3)	Near storm edge (2)	Storm edge (1)
Petite (1)	11 + <sup>a</sup>	7 - 10	4 - 6	1 - 3
Small (2)	16 +	11 - 15	6 - 10	1 - 5
Medium (3)	26 +	16 - 25	9 - 15	1 - 8
Large (4)	45 +	28 - 44	13 - 27	1 - 12
Gross (5)	67 +	34 - 66	18 - 33	1 - 17

<sup>a</sup>Flashes per cell.

Note: Time period, 8 h.

Cell Lightning Flashes								Cell Storm Size and Position Classification							
17	13	7	1	1	2	4	6	51	51	51	51	51	51	51	51
22	23	13	10	3	6	4	2	52	52	51	51	51	51	51	51
32	24	12	7	8	4	13	7	52	52	51	51	51	51	51	51
28	47	32	10	1	13	46	28	52	53	52	51	51	51	53	52
36	35	61	33	9	29	30	36	53	53	53	52	51	52	52	53
60	51	50	44	32	31	50	13	53	53	53	53	52	52	53	51
67	74	55	32	74	74	38	27	54	54	53	52	54	54	53	52
52	86	37	117	112	164	36	41	53	54	53	54	54	54	53	53
21	31	32	74	95	91	56	69	52	52	52	54	54	54	53	54
4	0	1	1	48	85	130	125	51	0	51	51	53	54	54	54

Figure 3. Storm activity within a single partition in northwestern Ontario (July 31, 1988).

Table 3. Proportion of continuous current flashes

Storm type		Storm center (4)	Near storm center (3)	Near storm edge (2)	Storm edge (1)
Petite	(1)	0.25	0.33	0.50	0.66
Small	(2)	0.20	0.25	0.33	0.50
Medium	(3)	0.15	0.20	0.25	0.33
Large	(4)	0.10	0.15	0.20	0.25
Gross	(5)	0.05	0.10	0.15	0.20

years of lightning occurrence studies and lightning-caused fire predictions. These studies have indicated that smaller storms have higher proportions of continuous current flashes than larger storms and that the edges of storms have higher proportions of continuous current flashes than storm centers. These proportions are used to calculate the total number of continuous current flashes in each cell over the 8 h time period.

#### (2) Rainfall Characteristics

Rainfall directly affects fuel moisture; consequently, it has a major influence on lightning-caused fire ignition. There are three aspects of rainfall that are important to the ignition process: the amount, the rate, and the duration. Fosberg (1972) found that the duration of rainfall was more important than either the amount or the rate. Fuels have a limited ability to absorb water over a short time period. Fuel sitting in a pool of water absorbs the water slowly. Long periods of even light rainfall extinguish most lightning-caused fires before they become detectable.

In a typical fire region, there are approximately 25 forest weather stations that

measure rainfall twice daily at 0800 and 1300. The rainfall from each station is associated with the most appropriate (often the nearest) cell. Because weather stations frequently represent areas exceeding 5 000 km<sup>2</sup>, the twice daily measurement of rainfall from a sparse network of rain gauges cannot adequately represent the amount or pattern of rainfall resulting from thunderstorms. Until Canadian forest fire control agencies implement networks of precipitation radar, accurate rainfall measurements will not be possible. At present, only crude estimates of the amount, rate, and duration of rainfall can be made.

Research has shown that there is a relationship between the number of cloud-to-ground lightning flashes and the amount of rainfall (Levin and Ziv 1974; Marshall and Radhakant 1978; Piepgrass et al. 1982). This relationship combined with total lightning flashes within a cell, rainfall amounts measured at weather stations, and the storm classification procedure described earlier is used to estimate storm rainfall patterns.

Each cell's storm size and position

classification, based on lightning flash counts (Table 2), are compared with the corresponding rainfall amount assigned from the nearest weather station. It is assumed that the lightning flash pattern more accurately reflects the true storm situation. A rainfall adjustment factor is applied to ensure that the rainfall and lightning patterns roughly match (Table 4). For example, the weather station may be located on the edge of a storm according to the lightning pattern. In this situation, rainfall amounts are increased for cells nearer the storm's center. This procedure improves rainfall amount estimates for individual cells and, consequently, improves fuel moisture estimates.

### (3) Existence of Combustible Fuels

The third element in the ignition process is the availability of combustible fuels that have the characteristics necessary to sustain ignition. Taylor (1969) found that lightning-caused fires originate in the fine fuels of conifer duff and litter under trees, in the "punky wood" of dead snags, and in the crowns of living trees. Latham and Schlieter (1989) developed ignition probability equations for eight fuel types found in the western

United States. These equations estimate ignition probability based on continuing current duration, flash type (positive or negative), fuel depth and moisture, and, to a limited degree, fuel bulk density. The eight fuel types include Ponderosa pine litter, Lodgepole pine duff, Douglas Fir duff, Engelmann spruce duff, peat moss, rotten chunky punky wood, punky wood powdered to a depth of 2.4 cm, and punky wood powdered to a depth of 4.8 cm. Ignition probabilities for short needle pines were primarily dependent on the depth of the fuel bed, whereas ignition probabilities for the other species were dependent on fuel moisture. Table 5 lists ignition probability equations by fuel type and type of lightning flash.

Fuel type information for the province of Quebec must be extracted from timber maps or low resolution satellite images. Only broad forest cover types are available, expressed as percentage coverage for each cell. In all, 27 fuel types are recognized in Quebec. Appendix 1 associates each type with an appropriate fuel type of Latham and Schlieter. The depth of each fuel type is estimated, whereas its moisture content is calculated based on adjusted rainfall.

Table 4. Assumed distribution of rainfall<sup>a</sup>

		Storm center (4)	Near storm center (3)	Near storm edge (2)	Storm edge (1)
Storm type					
Petite	(1)	1.0	0.3	0.2	0.1
Small	(2)	1.0	0.5	0.3	0.2
Medium	(3)	1.0	0.6	0.5	0.3
Large	(4)	1.0	0.8	0.6	0.5
Gross	(5)	1.0	0.9	0.8	0.6

<sup>a</sup>A rain gauge on the edge of a petite storm is assumed to measure one tenth (0.1) of that of a gauge located at the storm's center.

Table 5. Ignition probability equations (Latham and Schlieter 1989)

Fuel type	Negative flash	Positive flash
Ponderosa pine litter	$1.04 \times e^{-0.054 Mf}$	$0.92 \times e^{-0.087 Mf}$
Lodgepole pine duff	$(1 + e^{3.84 - 0.6 Df})^{-1}$	$(1 + e^{5.13 - 0.68 Df})^{-1}$
Douglas fir duff	$(1 + e^{5.48 - 1.28 Df})^{-1}$	$(1 + e^{6.69 - 1.39 Df})^{-1}$
Engelmann spruce duff	$0.8 - 0.014 Mf$	$0.62 \times e^{-0.050 Mf}$
Peat moss	$0.84 \times e^{-0.060 Mf}$	$0.71 \times e^{-0.070 Mf}$
Punky wood (rotten, chunky)	$0.59 \times e^{-0.094 Mf}$	$0.44 \times e^{-0.11 Mf}$
Punky wood (powdered to 2.4 cm depth)	$0.73 - 0.011 Mf$	$0.6 - 0.11 Mf$
Punky wood (powdered to 4.8 cm depth)	$0.9 \times e^{-0.056 Mf}$	$0.86 \times e^{-0.06 Mf}$

Notes: Mf is moisture content, valid between 0 and 40%; Df is duff depth, valid between 0 and 10 cm.

Flashes are assumed to be uniformly distributed over all forest cover types in the cell. The number of lightning flashes and their polarity in the cell are used to estimate the number of continuous current flashes terminating in each cover type. Adjusted rainfall for the cell (Table 4) and the Fine Fuel Moisture Code (FFMC) of the Canadian Forest Fire Weather Index System (Van Wagner 1987) are used to estimate the moisture content of each forest cover type. Using the relationships presented in Appendix 1 and the appropriate equations of Latham and Schlieter from Table 5, the expected number of ignitions in the cell are calculated.

### Smoldering Fire Component

The next step in the lightning-caused fire prediction process is to estimate the number of ignitions that will continue to smolder. If a fire is ignited during the evening or during the night, it must smolder at least until the next day's burning period if it is to become a detectable fire. Under typical weather and fuel moisture conditions in the Canadian boreal forest, most fires of this nature extinguish themselves during the first night. Even if they survive the night, they may remain relatively dormant during the day and may not begin to spread rapidly because of wet fuel conditions. If conditions are right for continued smoldering but too moist for the fire to spread rapidly, these fires may again survive in a smoldering state until the next day's burning period. Fires that have smoldered through one complete burning period are called holdover fires. Holdover fires caused by lightning 3 or 4 days earlier are common. Some have been known to smolder, undetected, for up to 10 days. To predict fire occurrences for the next burning period, therefore, it is necessary to consider all lightning flashes over the past 10 days.

Smoldering depends on the bulk density of the fuel and its moisture content. Based on field estimates using lightning flash counters, Kourtz (1974) established a strong relationship between the number of lightning flashes, the dryness of medium fuels before the storm, and the number of ignited fires. Further laboratory experiments lead to the development of a Smoldering Index (SMI) (equation [1]).

$$SMI = DC \times e^{\frac{-300}{(DMC)^2}} \quad [1]$$

This index uses the Duff Moisture Code (DMC) and Drought Code (DC) of the Canadian Forest Fire Weather Index System. SMI values below 75 indicate little chance of smoldering. Smoldering can take place at values above 100 and very dangerous situations occur at values above 200.

In addition to the factors considered by the SMI, ignition time, fuel type, fuel moisture content, and relative humidity are also important in determining the chance of a smoldering fire surviving to the next burning period. Eight equations were developed to reflect the chance of a fire surviving as a function of the SMI (Table 6).

Table 6. Survival probability equations

Level	Equation
Ultra low	$5.54 \log_e(SMI)$
Very low	$-19.0 + 11.13 \log_e(SMI)$
Low	$-38.5 + 16.72 \log_e(SMI)$
Moderate	$-58.0 + 22.31 \log_e(SMI)$
Average	$-77.5 + 27.90 \log_e(SMI)$
High	$-97.0 + 33.49 \log_e(SMI)$
Very high	$-116.5 + 39.08 \log_e(SMI)$
Extremely high	$-136.0 + 44.67 \log_e(SMI)$

Appendix 2 indicates the most appropriate survival equation to use based upon the ignition time, fuel type, FFMC, DMC, and relative humidity, fuel type being the most important factor. The chance of survival is also a function of when the fire was ignited. Holdover fires have the highest chance of survival because they have already smoldered under favorable fuel conditions for more than one burning period. Fires ignited during the day have a slightly higher chance of surviving until the evening than those ignited the previous night.

### Detectable Fire Component

It is the desire of fire control organizations to be able to predict the number and general location of visually detectable lightning-caused fires during the current or next burning period. This information can then be used to plan patrol routes for visual detection aircraft.

Many smoldering fires do not produce enough smoke to become visually detectable until their combustion rate accelerates to the point where flaming combustion is about to begin or actually begins. Timing of the detection effort is critical because most fires can only be detected

once the combustion rate begins to accelerate. Detection patrols detect few fires during periods of moist fuel conditions even though many fires may be smoldering. If fire control organizations delay the detection process until fuel conditions are quite dry, however, detection will be much easier but the fires may have entered a rapidly spreading phase, making them much more costly to suppress.

Infrared detection systems can detect up to a quarter of smoldering fires, especially during the night, thus significantly reducing the risk of late fire detection. The introduction of infrared detectors, however, will require that lightning-caused fire prediction systems emphasize smoldering fires rather than visually detectable fires. The modular ignition, smoldering, and detection structure of the prediction system described here is well suited to the use of infrared detection systems.

The ignition time of lightning-caused fires can be broken down into two groups. The first group involves ignition during the current day's burning period. Fires in this group may become detectable immediately and may not undergo a smoldering phase. Such is often the case in the intermountain area of British Columbia, where extremely dry fuels permit rapid spreading of a fire shortly after ignition. The second group involves fires ignited by lightning before the forecast burning period. Figure 4 illustrates the relationships among the various components of the detectable phase of lightning-caused fires.

The FFMFC, wind speed, temperature, and relative humidity determine whether or not fires will be detectable. At one extreme, on hot, dry, windy days with high FFMFC levels (low fine fuel moisture), fires are certain to be detectable. At the opposite extreme, on damp or foggy, cool days with calm winds, fires will remain in a smoldering state if they survive at all. Fires that do not become detectable during the present burning period have the potential to survive until the next burning period, at which time they once again may become detectable.

The chance of a fire being visually detectable is also related to the DMC and ignition period. Table 7 presents the level of detectability based upon the DMC and ignition period.

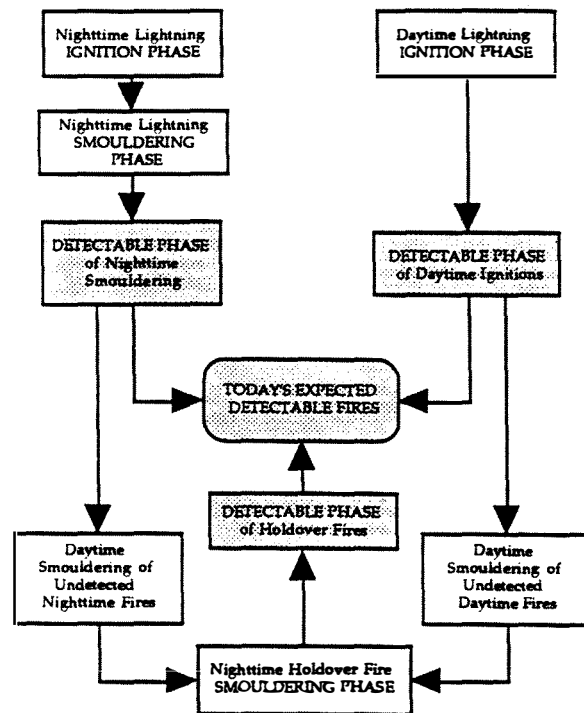


Figure 4. Elements of the detectable phase of lightning-caused fires.

Table 7. Detectability of lightning-caused fires

Level	DMC
Burning period or prior-night ignition	
Very low	0 - 20
Low	21 - 35
Moderate	36 - 50
Average	51 - 65
High	66 - 80
Very high	81 - 120
Extreme	121 +
Holdover fires burning more than 1 night	
Very low	0 - 19
Low	20 - 30
Moderate	31 - 39
Average	40 - 49
High	50 - 64
Very high	65 - 80
Extreme	81 +

The chance of a smoldering fire becoming detectable is a function of the Initial Spread Index (ISI), another component of the Canadian Forest Fire Weather Index System. The ISI relates the moisture of fine fuels and the wind speed to the rate at which a fire spreads. Table 8 presents seven

Table 8. Detectability equations

Level	Equation
Very low	$8.00 \log_e (ISI)$
Low	$13.07 \log_e (ISI)$
Moderate	$18.14 \log_e (ISI)$
Average	$23.21 \log_e (ISI)$
High	$28.26 \log_e (ISI)$
Very high	$33.35 \log_e (ISI)$
Extreme	$38.42 \log_e (ISI)$

equations that reflect the chance of detecting a fire as a function of the ISI. Detectability is scaled from 0 to 100, with 0 representing no chance of detection and 100 representing a fire that is certain to be emitting lots of detectable smoke.

### Creating a Fire Prediction Forecast

Modelling the chance of ignition, smoldering, and detectability resulting from each flash as it occurs throughout the day is not practical because of the inaccuracy of lightning, precipitation, and fuel information. Although the lightning location system instantly records data for flashes as they occur, a significant number are missed. For those that are recorded, position errors can be dozens of kilometres. Precipitation is reported only twice daily, at 0800 and 1300, from approximately 25 widely scattered weather stations. Fuel information derived from timber maps or satellite data is currently only available in a summarized form for each 50 km<sup>2</sup> cell in a forest region. Considering the poor data resolution, this prediction system is designed to make two forecasts daily: one at 0800, which covers the present day's burning period, and one at 1800, which predicts the number of fires that are expected to occur during the next day's burning period given the lightning forecast for that evening and night. Prediction forecasts can also be made as new lightning information becomes available. All predictions are based on the 50 km<sup>2</sup> regional cells.

The prediction process is initiated 10 days prior to the forecast day. That day's lightning activity is processed through the ignition, smoldering/survival, and detection phases. Those fires that are assumed to be detectable are removed. The remaining fires have the opportunity to smolder throughout the night. However, they may be joined by fires ignited by newly occurring lightning. Those smoldering fires that do not survive the night are removed.

Surviving fires continue to smolder into the next day's burning period. During this time, they may be joined by newly ignited fires. A portion of these may become detectable and are subsequently removed. At this point the process repeats itself. The cycle of new ignitions, smoldering, and removal as fires extinguish themselves or are detected continues to the forecast day. On the forecast day, the detectable fires represent the prediction. This process is illustrated in Figure 4.

The prediction process consists of seven steps.

**Step 1: *Getting the information.*** Weather, fire weather index, forest cover, and lightning flash information are obtained from the database information management system for each cell in the forecast region. Weather information is based on 0800 forecasts and 1300 actual readings. Lightning information is summarized for 8 h periods. These data are required for the previous 10 day period because of the possible existence of holdover fires.

**Step 2: *Determining the cell/storm relationship.*** The cell to storm relationship is determined by dividing the region into nine partitions. The total number of flashes and the percentage area that received lightning activity in each partition are used to categorize the storm into one of five storm size classes (Table 1). The storm size classification is then used with the number of flashes in each cell to determine the cell's spatial position within the storm, or the proximity of the cell to the storm's center (Table 2).

**Step 3: *Determining the number of long continuous current flashes and the amount of rainfall received at the cell level.*** The storm size classification and spatial position of each cell within the storm are used to derive the proportion of long continuous current (LCC) flashes (Table 3) and rainfall adjustment (Table 4) for the cell. The product of the proportion of LCC flashes and the number of flashes provides an estimate of the continuous current flashes that have the potential to start forest fires. To associate the rainfall pattern with the lightning pattern, each cell's storm size and position classification is compared with the corresponding rainfall measured at the nearest weather station. A rainfall adjustment factor is then applied to ensure that the rainfall and lightning patterns are similar.

**Step 4: *Determining the number of ignitions.*** Fuel type and moisture content are important in calculating the number of fires that will be ignited. Continuous current flashes are assumed to have an equal chance of hitting any point in the cell. The number terminating in each fuel type is proportional to the areal distribution of the fuels. The cell's fuel type coverage, the fuel types listed in Appendix 1, and the ignition probability equations presented in Table 5 are used to estimate the chance of ignition and the expected number of ignitions in each fuel type. The FFMC is used in the ignition probability equations for open pine litter, spruce duff, and peat moss, whereas the moisture content of the smoldering index is used for the three punky wood categories. Each fuel moisture content is calculated from the adjusted rainfall estimate.

**Step 5: *Determining the number of survivals.*** The next step in the prediction process is to determine the number of ignitions that will survive to the next burning period. The SMI is calculated for the cell using the DMC and DC values that were adjusted for rainfall. Eight survival equations (Table 6) reflect the chance of a fire surviving as a function of the SMI. The survival rate ranges from extremely high to ultra low. Appendix 2 lists the appropriate survival equation based upon the cell's fuel type, FFMC, DMC, and relative humidity (RH). For example, given a FFMC of 88, a DMC of 30, and a RH of 35, pine duff ignited during the nighttime period would have an extremely high survival rate. The product of the number of ignitions and the survival rate gives the expected number of fires that will survive to the next burning period for each fuel type.

There are three different survival situations that must be considered. The survival rate of ignitions that occur during the daytime period (0800 to 1800) is much higher than the survival rate of ignitions that occur during the nighttime period (1800 to 0800). In fact, daytime ignitions often advance directly into the detection phase. The third situation is the smoldering phase for holdover fires. The survival rate is highest in this category — holdover fires are assumed to be burning in a fuel complex protected from rain, a condition that is conducive to smoldering.

**Step 6: *Determining the number of detectable fires.*** The next step in the prediction process for a specific cell is to determine the number of

surviving fires that will become detectable during the burning period. Detectability is a function of the ISI, DMC, and ignition time. Seven equations have been developed to determine the chance of detecting a fire, varying from extreme to very low, depending upon the DMC and ignition time (Tables 7 and 8). Experience has shown that the time of ignition is a significant factor in determining detectability. Fires ignited during the burning period or during the night before are less likely to become detectable than those that have been in the holdover state for more than one night. Fuel type is not considered to be a major factor in detectability. It is assumed that fires burning in different fuel types have an equal chance of being detected. Fires that do not become detectable during the burning period smolder into the evening and possibly through to the next day's burning period at which time the cycle repeats (Figure 4). The lightning-caused fire prediction for the cell of interest is the number of fires that should become detectable during the forecast burning period.

**Step 7: *Producing a regional forecast prediction for the present burning period.*** Predictions of the number of lightning-caused fires that should occur within the region for the burning period of interest are made by summing the individual cell predictions. Probability statements, such as the probability of  $n$  or more fires occurring, can be made assuming that fire occurrence follows a Poisson distribution and that the summed cell predictions are a suitable Poisson parameter. These probability estimates are often more meaningful to the user than the predicted number of fires, which is a non-integer number, often less than one. Likewise, a confidence range can also be placed on the prediction. Such a statement is useful at lower levels of expected fire occurrence, but at higher levels this range can become too large and somewhat meaningless. This seems to indicate that the occurrence of large numbers of lightning-caused fires does not follow a Poisson-like distribution.

Table 9 provides a sample output of the lightning-caused fire prediction program for June 22, 1989, in the Outaouais region of Quebec. It attempts to summarize the available information at all stages of the prediction process. The first section summarizes the regional negative and positive lightning flash information recorded over

Table 9. Sample output of the prediction program

Lightning-caused fire prediction for June 22, 1989		
Lightning information for the last three time periods		
Yesterday (8 a.m. to 6 p.m.)		
Negative flashes	1079	
Positive flashes	39	
Last night (6 p.m. to 8 a.m.)		
Negative flashes	2521	
Positive flashes	33	
Today (8 a.m. to now)		
Negative flashes	4100	
Positive flashes	87	
Expected number of fire ignitions for last night's period		
Fires in holdover stage going into last night's period		14.4
Expected number of ignitions from last night's lightning		104.8
Total		119.2
Expected number of fire survivals for last night's period		
From last night's holdover fires		7.1
From last night's ignitions		75.7
Total		83.8
Expected number of fire ignitions for today's period		
Expected number of ignitions from today's lightning		55.7
Expected number of detectable fires for today's period		
From last night's holdover fires		4.1
From last night's ignitions		47.7
From today's ignitions		35.6
Total		87.4
Lower limit of expected detections		23.4
Upper limit of expected detections		167.7
Holdover fires that are likely to survive to the next burning period		33.5

three distinct time periods beginning the previous day. The next section summarizes information for the previous night: the number of holdover fires that existed at the beginning of the nighttime period and the number of ignitions that resulted from that night's lightning activity. The third section provides information on the survival of these ignited fires. The fourth section provides the expected number of ignitions from the current day's lightning activity. The fifth section provides estimates of the number of detectable fires originating from holdover fires, the previous night's newly ignited fires, and the current burning period's new ignitions. The Poisson

probability range of expected fire occurrence arrivals is also provided. The last section provides an estimate of the fires that should smolder throughout the present day and into the next burning period.

### Evaluating the Predictions

Table 10 compares lightning-caused fire predictions for 5 days in 1989 in the Quebec-Mauricie region of Quebec. The table lists the number of lightning flashes received during the previous night (1800 to 0800) and during the current day (0800 to 1800). Four storm sizes are

Table 10. Comparison of lightning-caused fire predictions for 5 days in the Quebec-Mauricie region of Quebec

Date	Previous night's lightning (1800 to 0800)	Current day's lightning (0800 to 1800)	Predicted fires	Actual fires
June 24, 1989	65	160	5.5	7
July 25, 1989	433	2728	40.3	24
July 26, 1989	101	25	4.4	5
July 27, 1989	270	5196	77.0	7
August 30, 1989	127	1711	5.1	5

represented ranging from small to gross. In all cases, afternoon lightning occurred.

The prediction for June 24 relates to a small storm that occurred in the northwestern quadrant of the region during the early part of the day — the prediction is fairly accurate. The predictions for July 25 to July 27 cover a 3 day period of lightning activity. The large storm on July 25 occurred during the early afternoon and covered two thirds of the region. Real-time precipitation data for the period were not available, hence the predicted number of fires was high. The prediction for July 26, however, was fairly accurate, indicating that the 1 day smoldering/survival function was working. The prediction for July 27 relates to a gross storm that occurred during the late afternoon. Because rainfall measurements were once again unavailable, the prediction system failed and produced inaccurate results. The prediction for August 30 relates to a small to medium storm that occurred during the early morning — the prediction is accurate.

The prediction system produces fair to good results for small to medium morning storms and medium to large overnight storms. As well, the 1 day smoldering/survival function seems to work well. Poor predictions are generated, however, from large or gross afternoon storms, when rainfall and fuel moisture content data are not available, and from the smoldering function in excess of 2 days.

#### Summary

The prediction system described here uses lightning flash information, fuel type information, ignition probability estimates, and general lightning-caused fire behavior knowledge to forecast expected lightning-caused fire occurrences for the following day in a large forested region. This is accomplished by

partitioning a large region into cells approximately 50 km<sup>2</sup> in size. Based upon lightning activity in each partition, the size of lightning storms is classified. Using the storm size classification and the number of flashes within each cell, the position of the cells within the storm is classified. The storm size and spatial components for each cell are then used to estimate the proportion of continuous current flashes. Each cell's storm size and position classification are then compared with rainfall data from the nearest weather station. A rainfall adjustment factor is then determined to ensure that rainfall and lightning patterns match. The number of expected ignitions for each fuel type in each cell is then estimated. Next, the number of ignitions expected to survive as smoldering fires is estimated. Here, holdover fires, surviving from as far back as 10 days, are combined with new smoldering fires. Finally, an estimate is made of the number of smoldering fires that should become detectable during the forecast burning period. The end result is a lightning-caused fire prediction for each cell. The fire predictions for each cell are then summed and mapped to provide a regional fire prediction forecast.

There are many weaknesses in the lightning-caused fire prediction process. Inaccurate lightning flash numbers and locations are a significant problem. Inadequate knowledge of smoldering and survival processes is another problem area. This system uses many expert opinions on the nature of various processes in an attempt to overcome the poor quality of the data and the lack of knowledge of the true processes. In spite of these shortcomings, lightning-caused fire prediction forecasts have been quite reliable. The system seems to provide adequate forecasts for large, general, overnight and early morning storms. The prediction of expected fire arrivals is fairly close to actual fire occurrences. However, predictions are poor for late afternoon storms.

These storms occur after weather stations have recorded their afternoon rainfall measurement. Because of inaccurate rainfall information, fuel moisture estimates are also incorrect; therefore, fire predictions are poor. The prediction system is also weak in modelling holdover fires and survival rates of fires over periods longer than 1 day. Further basic research is required in these areas. More accurate and detailed flash sensor information, real-time precipitation radar data, and digital timber inventory information, as well as incorporating expert system and neural networks into the analysis and use of the information, would improve predictions. Until such time as these improvements are made, this process will provide a short-term solution to lightning-caused fire prediction.

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**Appendix 1. Relationship between Quebec fuel types and those of  
Latham and Schlieter (1989)**

Quebec fuel type	Latham and Schlieter fuel type			
<b>Softwood</b>				
Regeneration	Peat moss			
Young	Pine litter			
White pine	Pine duff			
Other pines with intolerant hardwood	Pine duff			
Mature stands	Pine duff			
<b>Mixedwood</b>				
Regeneration	Peat moss			
Young	Spruce duff			
Trembling aspen with softwood	Spruce duff			
White pine with intolerant hardwood	Spruce duff			
Other pines with intolerant hardwood	Spruce duff			
White/yellow birch with softwood	Spruce duff			
Mature stands	Spruce duff			
<b>Hardwood</b>				
Regeneration	Rotten	Chunky	Punky	Wood
Young	Rotten	Chunky	Punky	Wood
Intolerant	Rotten	Chunky	Punky	Wood
White/yellow birch	Rotten	Chunky	Punky	Wood
Trembling aspen	Rotten	Chunky	Punky	Wood
Maple/birch	Rotten	Chunky	Punky	Wood
Mature stands	Rotten	Chunky	Punky	Wood
Uncultivated or fallow land	None			
Burned areas	None			
Total cut	Pine litter			
Insect and disease damage	Fir duff			
Plantation	Peat moss			
Swamps	None			
Agricultural	None			
Water	None			

**Appendix 2. Survival equations based upon the fuel type,  
Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC),  
and relative humidity (RH)**

Fuel type	FFMC	DMC	RH	Survival equation <sup>a</sup>
<b>Daytime ignition fires</b>				
Open pine litter	0 - 79	0 - 14	56 +	Very low
	80 - 83	15 - 19	46 - 55	Low
	84 - 87	20 - 29	36 - 45	Moderate
	88 - 91	30 - 39	26 - 35	Average
	92 +	40 +	0 - 25	High
Pine duff	0 - 74	0 - 14	56 +	Moderate
	75 - 79	15 - 19	46 - 55	Average
	80 - 84	20 - 26	41 - 45	High
	85 - 88	27 - 32	31 - 40	Very high
	89 +	33 +	0 - 30	Extremely high
Fir duff	0 - 74	0 - 14	56 +	Low
	75 - 79	15 - 19	46 - 55	Moderate
	80 - 84	20 - 26	41 - 45	Average
	85 - 88	27 - 32	31 - 40	High
	89 +	33 +	0 - 30	Very high
Spruce duff	0 - 74	0 - 14	56 +	Very low
	75 - 79	15 - 19	46 - 55	Low
	80 - 84	20 - 26	41 - 45	Moderate
	85 - 88	27 - 32	31 - 40	Average
	89 +	33 +	0 - 30	High
Peat moss	0 - 79	0 - 19	46 +	Ultra low
	80 - 84	20 - 26	41 - 45	Very low
	85 - 88	27 - 32	31 - 40	Low
	89 +	33 +	0 - 30	Moderate
Punky wood	0 - 74	0 - 14	56 +	Low
	75 - 79	15 - 19	46 - 55	Moderate
	80 - 84	20 - 26	41 - 45	Average
	85 - 88	27 - 32	31 - 40	High
	89 +	33 +	0 - 30	Very high
<b>Nighttime ignition fires</b>				
Open pine litter	0 - 79	0 - 14	56 +	Ultra low
	80 - 83	15 - 19	46 - 55	Very low
	84 - 87	20 - 29	36 - 45	Low
	88 - 91	30 - 39	26 - 35	Moderate
	92 +	40 +	0 - 25	Average
Pine duff	0 - 79	0 - 14	56 +	Average
	80 - 83	15 - 19	46 - 55	High
	84 - 87	20 - 29	36 - 45	Very high
	88 +	30 +	0 - 35	Extremely high

Appendix 2. (cont'd)

Fuel type	FFMC	DMC	RH	Survival equation <sup>a</sup>
Fir duff	0 - 79	0 - 14	56 +	Moderate
	80 - 83	15 - 19	46 - 55	Average
	84 - 87	20 - 29	36 - 45	High
	88 +	30 +	0 - 35	Very high
Spruce duff	0 - 79	0 - 14	56 +	Very low
	80 - 83	15 - 19	46 - 55	Low
	84 - 87	20 - 29	36 - 45	Moderate
	88 - 91	30 - 39	26 - 35	Average
	92 +	40 +	0 - 25	High
Peat moss	0 - 83	0 - 19	46 +	Ultra low
	84 - 87	20 - 29	36 - 45	Very low
	88 - 91	30 - 39	26 - 35	Low
	92 +	40 +	0 - 25	Moderate
Punky wood	0 - 79	0 - 14	56 +	Low
	80 - 83	15 - 19	46 - 55	Moderate
	84 - 87	20 - 29	36 - 45	Average
	88 - 91	30 - 39	26 - 35	High
	92 +	40 +	0 - 25	Very high
<b>Holdover fires</b>				
Open pine litter	0 - 79	0 - 14	56 +	Very low
	80 - 83	15 - 19	46 - 55	Low
	84 - 87	20 - 29	36 - 45	Moderate
	88 +	30 +	0 - 35	Average
Pine duff	0 - 74	0 - 10	46 +	Average
	75 - 79	11 - 14	41 - 45	High
	80 - 83	15 - 19	36 - 40	Very high
	84 +	20 +	0 - 35	Extremely high
Fir duff	0 - 74	0 - 10	61 +	Moderate
	75 - 79	11 - 14	56 - 60	Average
	80 - 83	15 - 19	46 - 55	High
	84 - 87	20 - 29	36 - 45	Very high
	88 +	30 +	0 - 35	Extremely high
Spruce duff	0 - 79	0 - 14	56 - 60	Low
	80 - 83	15 - 19	46 - 55	Moderate
	84 - 87	20 - 29	36 - 45	Average
	88 +	30 +	0 - 35	High
Peat moss	0 - 79	0 - 14	56 +	Very low
	80 - 83	15 - 19	46 - 55	Low
	84 - 87	20 - 29	36 - 45	Moderate
	88 +	30 +	0 - 35	Average
Punky wood	0 - 79	0 - 14	56 +	Average
	80 - 83	15 - 19	46 - 55	High
	84 - 87	20 - 29	36 - 45	Very high
	88 +	30 +	0 - 35	Extremely high

<sup>a</sup>Refer to Table 6 for actual equation.

# APPLICATION OF FIRE OCCURRENCE PREDICTION MODELS IN ONTARIO'S FIRE MANAGEMENT PROGRAM

Al Tithecott<sup>2</sup>

## INTRODUCTION

Forest fire managers must make decisions about the deployment of expensive fire fighting resources using uncertain predictions of fire danger. Fire Danger is a term that encapsulates the status of the forest fire environment at any time. There are four major components of fire danger:

- weather,
- forest fuels,
- topography, and
- risk of fire occurrence. (see Figure 1.)

Fire weather forecasts have been a key component of daily planning since 1925 (CFS, 1987). The fuel moisture codes and fire behaviour indices of the Canadian Forest Fire Weather Index (CFFWI) are used with weather forecasts extensively across the country and we can say that our understanding of forest fuel hazards and fuel moisture is rather well developed in Canada. Topography is included in the fire behaviour models of the Fire Behaviour Prediction System (CFFBPS) (Forestry Canada, 1992). Our understanding of near and medium term risk is much less developed. The prediction of both hazard and risk are important components of daily planning in Ontario's fire management program.

Computer models that predict expected number of fires in Ontario's regions and districts have been developed. This work has been ongoing since the early 1970's. The sections that follow will describe the role of fire occurrence prediction models in Ontario, our experience with prediction models since 1986, and where we might want to go in this area.

You may see "Fire Occurrence Prediction" and "Fire Arrival Prediction" used interchangeably in this and other discussions. There are important differences between the two.

Forest fires "occur" when an ignition takes place and fire from that ignition will spread in forest fuels if left unattended. Detection systems search for undetected fire occurrences. Occurrences may or may not be detectable because of burning conditions or visibility (haze).

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<sup>1</sup> Presentation made at Eighth Central Region Fire Weather Committee Scientific and Technical Seminar, April 3, 1992, Winnipeg, Man.

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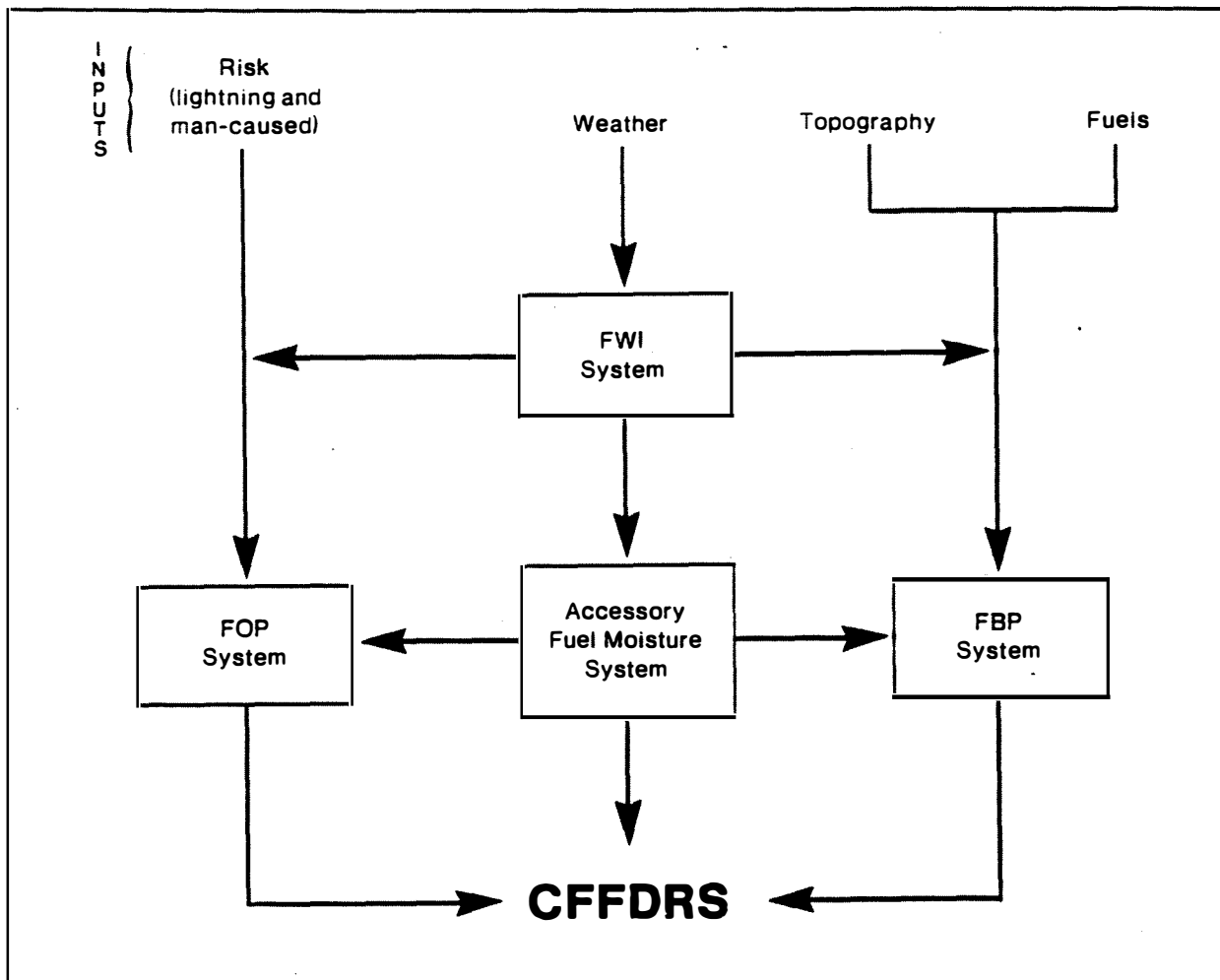


Figure 1. Structure of the Canadian Forest Fire Danger Rating System. (CFS, 1987)

A forest fire "arrives" when an occurrence is reported to the agency responsible for action. Fire protection agencies plan for arrivals. In most cases, people-caused fires occur and arrive in the same day and modelling techniques are similar for both occurrences and arrivals. Lightning fires often arrive some days after they occur because of the burning conditions after lightning activity. For lightning fires, then, the modelling of both occurrence and arrival processes is critical and separate. (Todd, 1992.)

In Ontario, Regional Fire Centres are responsible for planning daily preparedness and for decision-making during the day. Every

regional Fire Duty Officer (FDO) is supported by a Fire Intelligence Officer (FIO). The FIO serves in several capacities in the Fire Centre but there are two principle roles the FIO fills that are related to fire occurrence:

1. The FIO brings together information and knowledge about forecast weather, lightning, fuels, fire behaviour, season of the year, the people in the forest, values in the region, etc. to predict fire arrivals for the coming fire day (or days).
2. The FIO accumulates occurrence and behaviour information about new and ongoing fires to keep decision makers in all other parts of the program aware of the nature of the fire problem that exists.

Because the FIO develops predictions and also monitors incoming arrivals, there is a short term process of "intuitive verification" that allows the FIO to take advantage of recent knowledge about fire occurrence to predict future fires. The FIO develops a good understanding of historical causal agents active in the forest, the relationships between fuel moisture and fire occurrence, and the number of fires that have arrived recently. Because of the cognitive ability of the FIO to synthesis complex information from many sources, the experienced FIO cannot be completely replaced with computer-based fire arrival prediction models.

However, there are a number reasons why the FIO needs fire arrival prediction models to support the daily planning process:

1. Time - The FIO must predict fire occurrence over a large area for up to five days in the future. Often these predictions must be made in a few minutes between the time a fire weather forecast is available and planning sessions begin.
2. Consistency - Experience and understanding varies among the people who act as regional FIO's. This can lead to highly variable predictions from day to day or region to region.
3. Sudden changes - When an FIO returns from days off or fire weather changes quickly, the FIO does not have the advantage of short-term experience to assist with decision-making.
4. Inexperience - Inexperienced FIO's will not have detailed understanding of fire occurrence patterns in the region and the relationship of those patterns to weather, season of the year, etc.
5. Advanced decision support tools - Advanced decision support models require predictions of fire occurrence. Often this prediction must be stated as an expected value or probability or may be required by cell or sub-region. FIO's can make good general predictions but have difficulty producing reasonable expected values or probabilities for small areas, particularly given the time constraints on daily planning.

## MODEL EVALUATIONS IN ONTARIO

The models that are described below, while modified and applied in Ontario, have been developed elsewhere. PEOPLE, SPARKY, and FUZZY were developed at Petawawa National Forestry Institute by Dr. Peter Kourtz, Bernie Todd, Bernie Mroske, and Bernie Roosen. The presentation at this seminar by Bernie Todd (Todd, 1992) and the paper by Todd and Kourtz (1991) represent the latest PNFI work that has been used in Ontario. Dr. David Martell of the University of Toronto has been involved in fire occurrence research since 1973 and has produced various models that indicate the probability of fire occurrence. The work reported in Martell, Bevilacqua, and Stocks (1989) represents the latest development in that work. These two groups are leaders in North America, if not the world, in the area of fire occurrence prediction.

Ontario has worked principally with two people-caused fire prediction models in the last 5 years:

1. The PEOPLE fire occurrence prediction model was developed at the Petawawa National Forestry Institute (PNFI) to predict people-caused forest fires based on an analysis of historic fire and weather data (see Todd and Kourtz, 1991). An analysis of the fire and weather history for individual "cells" in each region is used to produce prediction parameters. (Cells are 20 kilometre by 20 kilometre areas.) The PEOPLE program uses historical cell parameters and forecasted weather (FFMC, DMC, and wind speed) to calculate expected numbers of fires for each cell in the region. The individual cell predictions are summed to give the fire manager a regional expectation for the day. The processes of parameter development and daily prediction are described in Todd and Kourtz (1991). Fire managers are given an estimate of the number of people-caused fires to expect and confidence limits for the prediction. The cell-based prediction process used in PEOPLE allows predictions to be displayed in map form. The spatial distribution of predictions can be valuable for priority setting and advanced modelling. Figure 2 shows a typical comparison of daily model predictions and actual fire arrivals over a fire season.

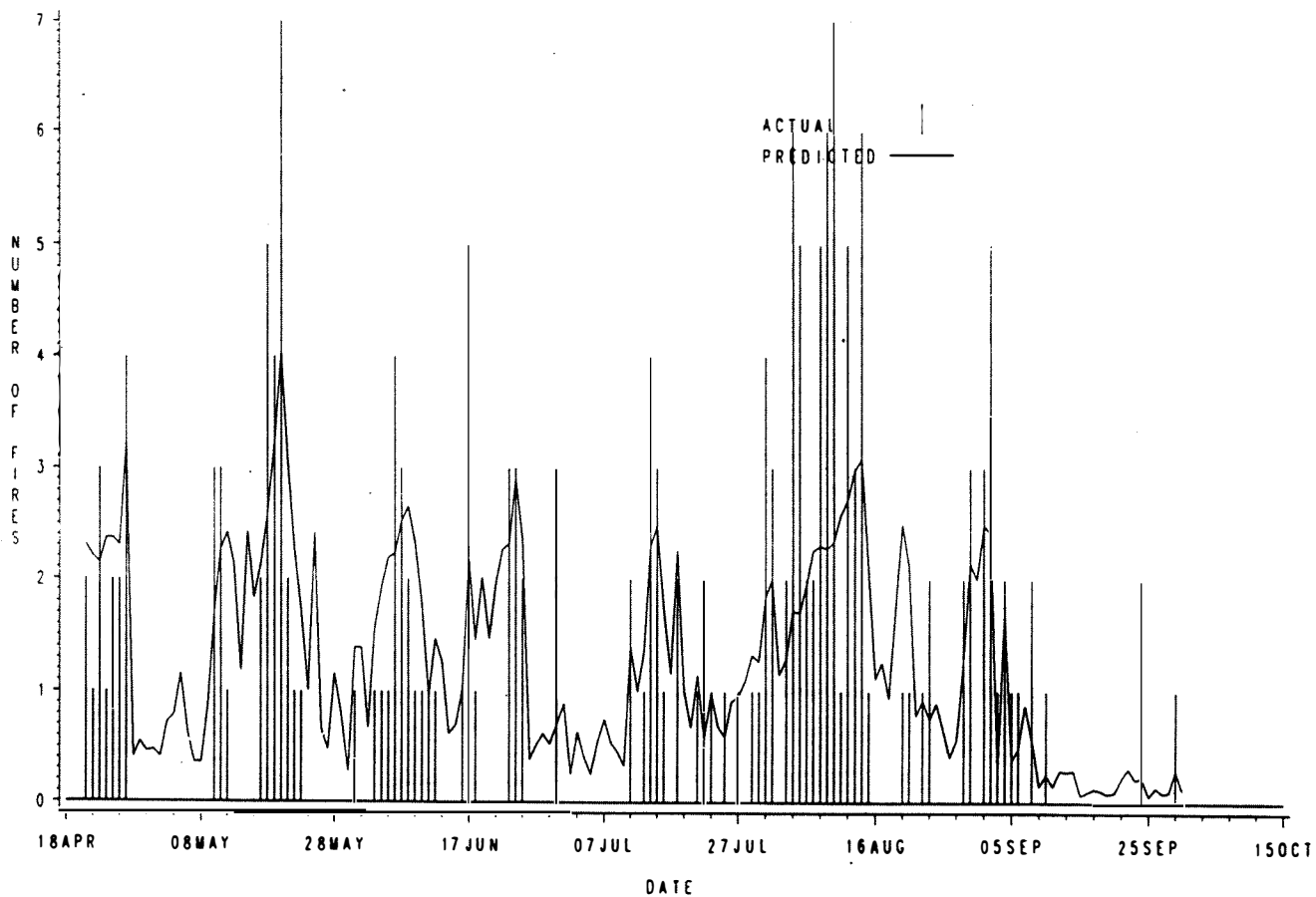


Figure 2. Prediction of Number of Fires using the PEOPLE Model Northcentral Region, 1991.

2. Dr. David Martell and his associates at the University of Toronto have developed a series of models that predict people-caused fire occurrence (Martell et. al. 1985, 1987, and 1989). Logistic regression models that account for seasonal variation in occurrence and differences between causal groups have been evaluated in Ontario since 1989. (Simpler models from the same research program were evaluated in Ontario in the 1970's and 80's.) If a "fire day" is defined as a day when one or more people-caused fires occur, logistic regression of the historical fire and weather data can be used to estimate the probability that a "fire day" will occur. Figure 3 shows the typical relationship between FFMC and the probability of a fire day. Seasonal variation in occurrence rates is obvious in the figure.

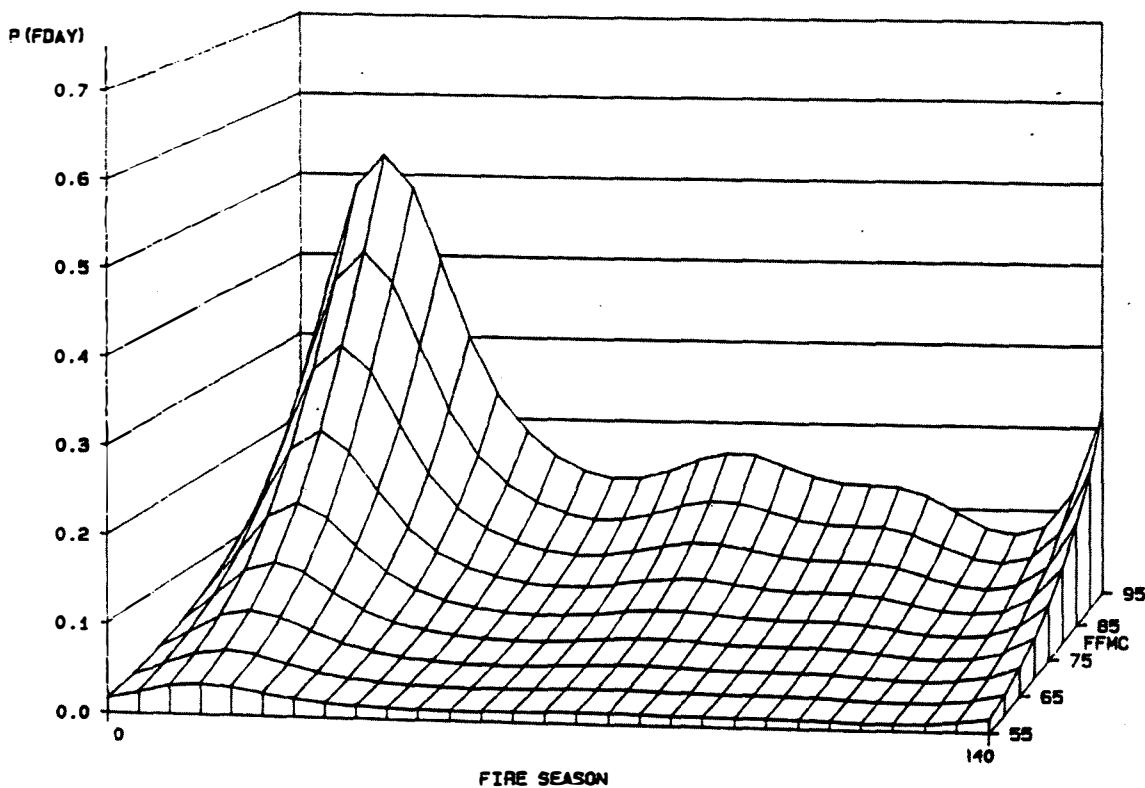


Figure 3. Probability of a Fire Day in Kenora District.  
(Causes RES, RWY, MIS, and UNK when BUI = 30)

One weather station is used to represent the daily weather for each district in a region. The independent variables FFMC, BUI, and day of the fire season are used to produce daily fire occurrence predictions. Using the assumption that daily occurrence is a Poisson process, the expected number of fires for the day can be estimated from the probability of a fire day. Figure 4 shows a typical season of regional predictions using these models.

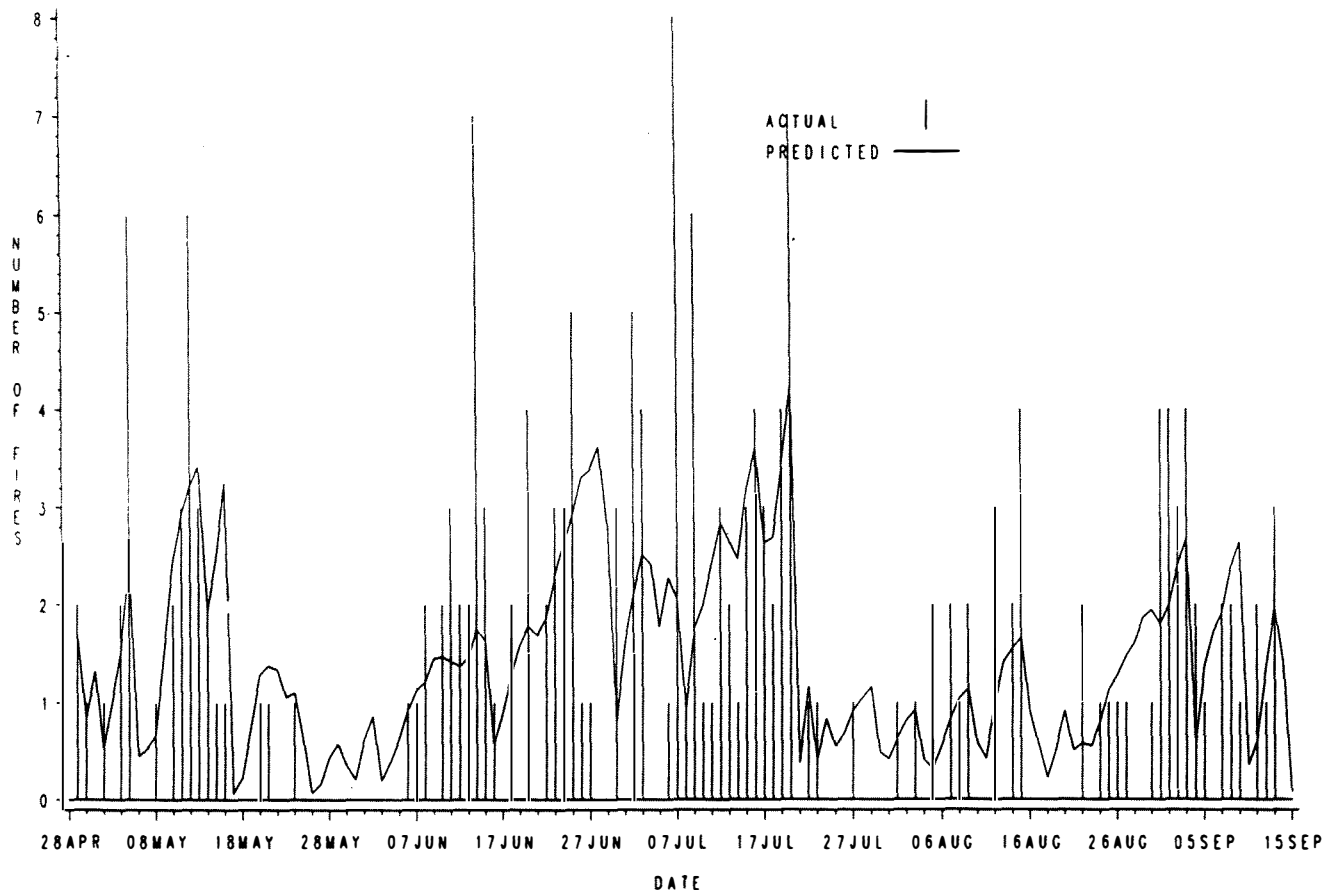


Figure 4. Prediction of Number of Fires using Logistic Regression Models, Algonquin Region of Ontario, 1991.

Our experience with these two people-caused models has demonstrated that, despite their very different approaches to the problem, they have similar strengths and weaknesses. This would suggest the problems are related to the nature of people-caused fire occurrence. Figure 5, for example, shows the predictions of both models and the actual fire arrivals in the Northwestern Region in 1989.

Predictions from a good statistical model will equal the actual number of fires **over the long run**. In our 1989 evaluations of these models in the Northwestern region of the province, we found this to be the case. Both PEOPLE and the logistic regression models had similar errors over the long term and neither model has exhibited systematic seasonal bias over the last 3 seasons. Because of this, FIO's have confidence that both models provide a **reasonable estimate** of the number of people-caused fires to expect.

However, we expect a model to produce a good indication of the nature of the individual days that are coming; we expect the model to capture as much of the daily variation as possible. This is a difficult task with people-caused fires because the model has no direct measure of the activity of the causal agents and the daily variation in the number of fires is very large. As expected, the models do best under moderate conditions and both of these models tend to under-predict the days when many people-caused fires occur in the region. These days are rare in most regions and this result might be expected from simple models. Since unexpected fire arrivals under low conditions are usually not difficult for the fire program to respond to, the inability to predict the most severe days is the most important shortcoming in the current generation of models.

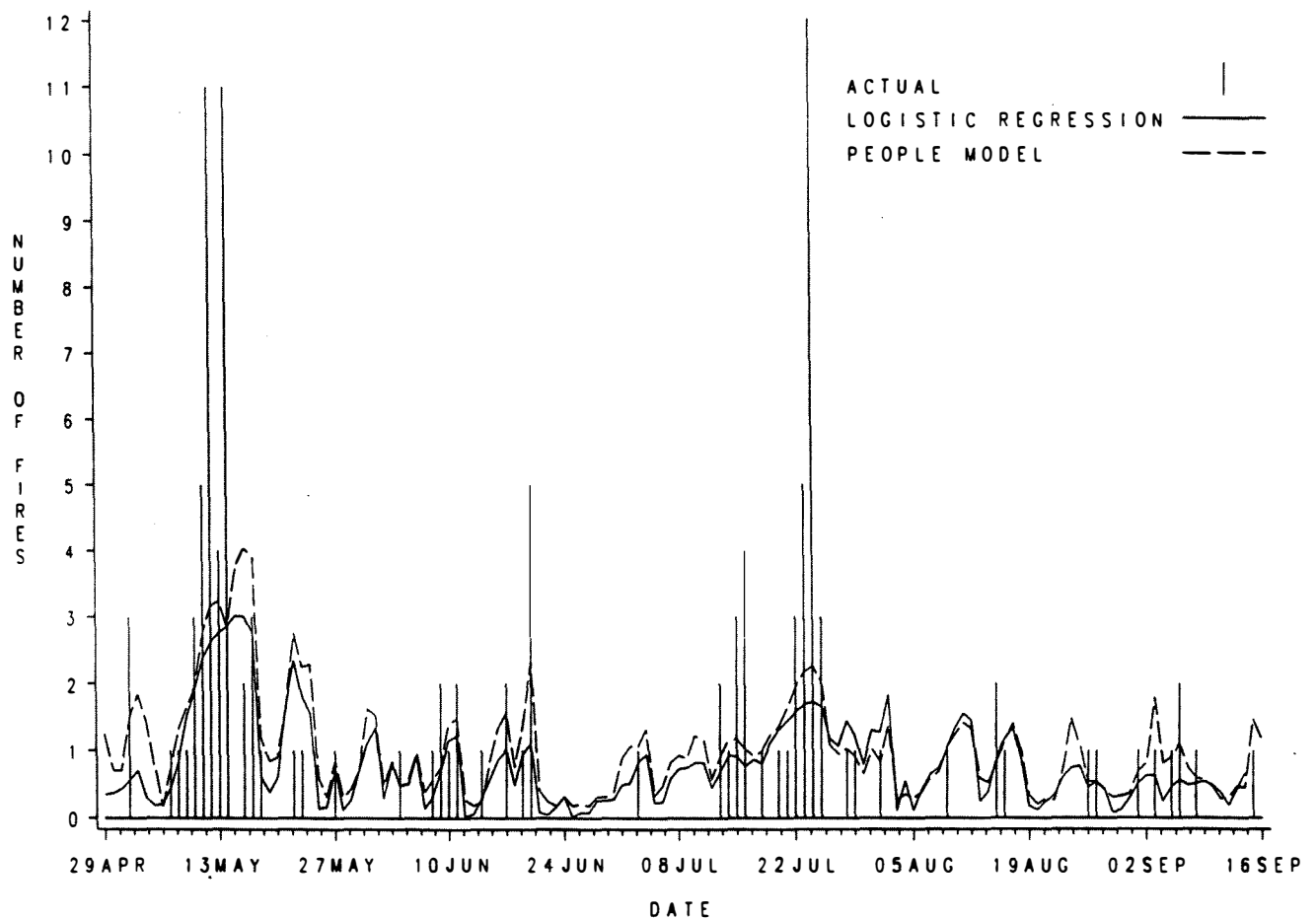


Figure 5. Comparison of Two People-caused Fire Arrival Prediction Models, Northwestern Region, 1989.

Lightning fires are a greater fire prediction problem in Ontario than people-caused fires. Lightning fires tend to arrive over many days after lightning activity and in remote locations. As well, the fact that many lightning fires can arrive in one burning period can quickly test the initial attack capability of the fire organization. The existence or absence of potential lightning arrivals causes considerable anxiety in the daily planning process.

Ontario has evaluated only one lightning fire prediction model\*. SPARKY was developed at PNFI by Todd, Kourtz, Mroske, and Roosen. This model has been described by Bernie Todd at this seminar (Todd, 1992). The process used in SPARKY is its major strength; ignition, survival and arrival are all modelled individually. Advances in affordable computing power provide any fire organization with the capability to use this kind of modelling approach. The version of SPARKY that will be used in Ontario in 1992 is slightly different than the one described by Todd (1992). The Ontario version takes advantage of new lightning detection efficiency information and weather interpolation. The model has also been re-aligned to predict only new fires that might occur in a 24 hour period ending at 08:00.

Figure 6 shows daily predictions of new fire occurrences and actual fire arrivals in the Northwestern Region in June of 1991. There has been detailed discussion of the operation of SPARKY in the previous session (Todd, 1992).

Ontario's experience with SPARKY can be summarized as follows:

Regional FIO's find SPARKY to be useful for estimating the new occurrences that might arrive from lightning that occurred during the last 24 hours.

The overnight fire survival part of the model is biased towards fire extinguishment. That is, the model is biased against the prediction of holdover fires.

The approach taken in SPARKY considers all lightning storms to be the same. This means the number of lightning flashes influences the prediction greatly and the model "under-predicts" fires from small convective cells and "over-predicts" fire occurrence when large storm systems pass through.

\* An expert system to predict fires from all causes was evaluated in Ontario in 1989. While the applicability of this technology was demonstrated, software and hardware capability at the time limited the usefulness of the model for daily planning. We expect that new generations of models along this line will be developed at PNFI.

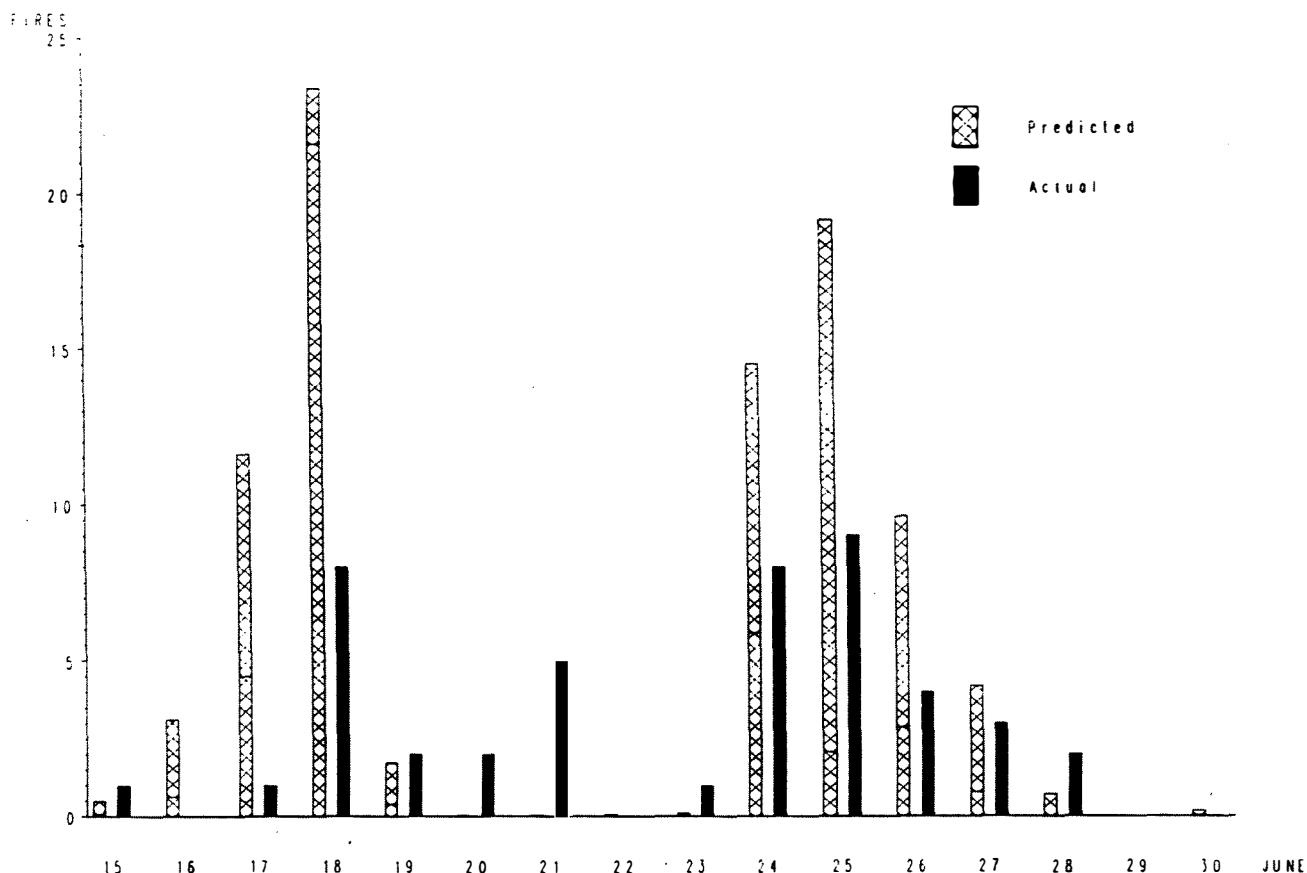


Figure 6. Predictions of New Lightning Fires using a Revised SPARKY Model, Northwestern Region of Ontario, June 1991. (The hatched bar represents predicted occurrences with a lower line showing predicted arrivals.)

#### OPERATIONAL USE OF PREDICTION MODELS

The introduction of statistical models to a forest fire management organization requires that the users of the models understand "error" and the significance of error to the job at hand. Predictions are usually presented as an expected number of fires, as a range of possibilities, or as a probability distribution. A simple estimate of the number of fires hides the large amount of variation inherent in forest fire occurrences and arrivals. Confidence intervals or probability distributions are the best way to portray the information. If users are uncomfortable with the concepts of probability or confidence intervals, models should not hide the error estimates. Model users must come to understand error and probability to be able to accept, understand, and use stochastic prediction models.

When a prediction model is introduced to an operational organization, two attitudes will predominate: some users will naively trust the model and others will be completely sceptical of the model until some experience has been gained. The completely trustful user will probably switch completely to be completely sceptical when the first "bad prediction" is encountered.

To avoid these directly opposite and exclusive attitudes, users require a good understanding of the nature of:

- errors in prediction models,
- the difference between error and bias,
- the development of the model to be used, and
- the performance of the model when tested.

Ultimately, users prefer to evaluate model performance in an operational setting before they will trust model predictions. When errors and the contents of "black box" are not understood, trust will be built slowly by reliable predictions and destroyed quickly by poor or poorly understood predictions.

FIO's in Ontario see the models we use in our fire centres as reasonable estimates of what to expect. They also maintain healthy scepticism of the predictions and rely on their own judgement in the final analysis of every situation. All users of these models must understand that the models give them an accounting of the historical fire and weather record and insight into the problem at hand but do not represent "the answer". The models being used in Ontario have not evolved to the point that they can challenge the good judgement of an FIO.

We must, then, be wary of the role we expect prediction models to take in operational fire management. For the reasons stated above, fire occurrence prediction models are required in the FIO's tool kit alongside weather forecasts and the fire behaviour prediction system. However, we must keep in mind the limits to which statistical models should be developed to replace the process the FIO undertakes. Models should represent a sound and stable base for planning and the FIO should be trained to understand the limits of models and to account for the day to day complexities of the prediction problem. Predictions are designed to reduce anxiety in planning and decision-making and the trust of the person making decisions is the ultimate test of the success of a prediction system.

This issue of trust has important implications in the use of fire occurrence predictions. When predictions are used in advanced decision support models, the FIO must have "ownership" of the prediction before it is used in other models. For example, a model is being developed to estimate the requirement for airtankers on a daily basis. One of the requirements of this deployment model is an estimate of the number of fire arrivals the airtanker system will be responding to. This prediction is distributed temporally throughout the day as well as spatially across the region or province. In today's computer environment, the deployment model could extract fire arrival predictions and fire behaviour estimates directly from other models and/or computer files. In our experience, the advanced planning model should not take information directly from other models. The FIO must have direct control over the inputs to the deployment model in order to have ownership over the answer from the deployment model. The FIO can also try a range of predictions in the deployment model to evaluate the implications

of error in his occurrence prediction. The FIO has the cognitive ability to synthesize information from support tools such as fire occurrence models and use the deployment model to analyze his problem. In Ontario, we will still rely on the FIO's ability to synthesize information into a realistic and trusted plan.

#### **WHERE CAN WE GO FROM HERE FOR BETTER PREDICTIONS?**

We have identified a few areas where the current generation of prediction models are weak. Can predictions be improved? Certainly there is a large amount of natural variation in the processes that cause forest fires and we can never expect to predict all fire situations all of the time. We must regularly re-assess the additional value of model improvement in light of the cost of new research or technology. However, we expect FOP models can and should evolve further.

People-caused fire occurrence continues to challenge researchers. There are opportunities to improve the accounting of seasonal fluctuations in people-caused fire occurrence, and to better predict the number of people-caused fires on multiple fire days (account for more daily variation). There are also a number of opportunities to take advantage of differences in occurrence patterns related to fire cause. For example, trends in people-caused fire occurrence are of interest to the fire manager for longer term planning, particularly related to fire prevention. Figure 7 shows the annual number of railway fires in Wawa District of Ontario. We can see a large variation in the annual number of fires. One year (1980) apparently has an unusually large number of fires. A large amount of this variation is caused by seasonal weather severity. We can develop a daily fire occurrence regression model using data from the years 1965 to 1980 to account for most of the annual variation in weather over that period. As we expect with a good prediction model, the difference between the actual number of fires and the prediction over a fire season is relatively small and unbiased over the model period (See Figure 8). More important, however, is the annual difference between the predicted and actual occurrences after 1980. We can see that there is a systematic departure of actual occurrences from the prediction over the period 1981 to 1990 that represents a decreasing trend in the number of railway fires after 1980 (Figure 8). We also see that the apparent anomaly in 1980 was predicted by the model. This result demonstrates three important points:

1. the analysis of a specific cause grouping has brought out important information,
2. these fire occurrence prediction models can be used to analyze trends in people-caused fire occurrence, and
3. a daily prediction model for use operationally should account for long term trends and the model builder should be wary of historical data that does not represent the current situation.

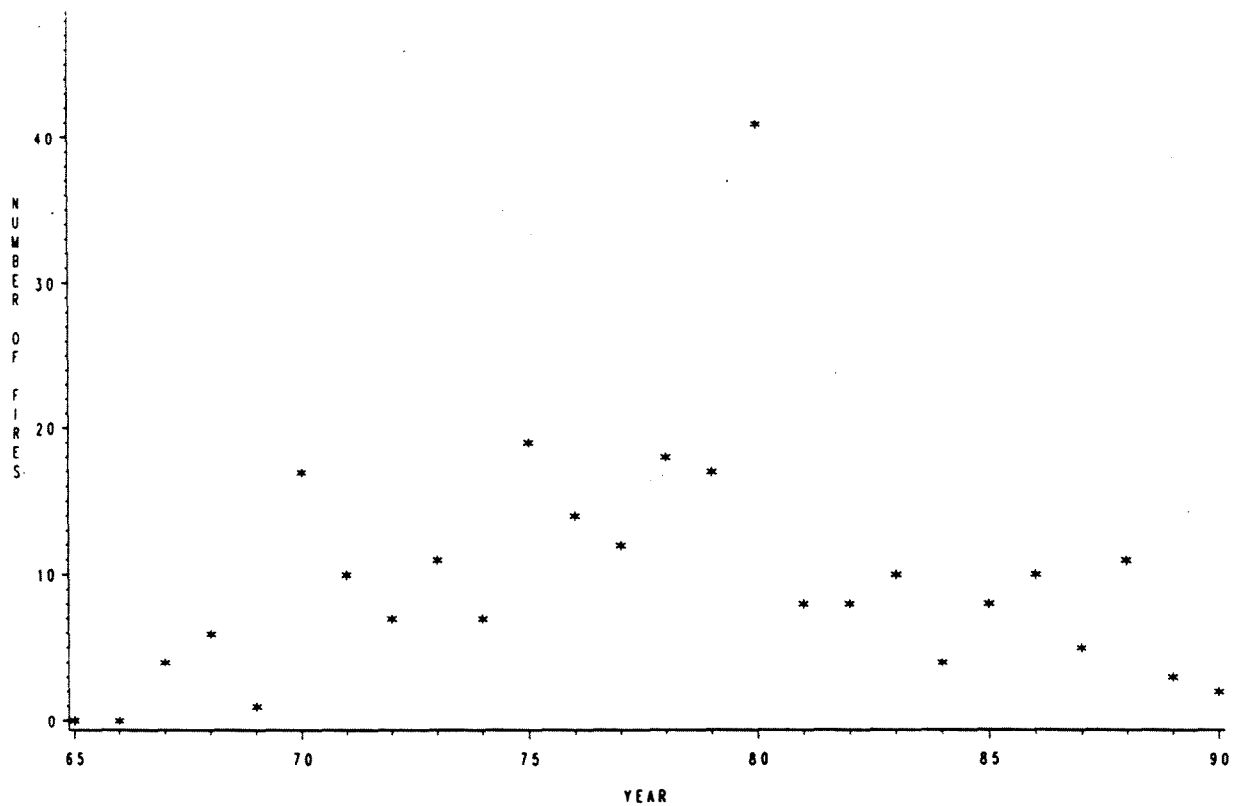


Figure 7. Annual Railway-caused Forest Fires, Wawa District

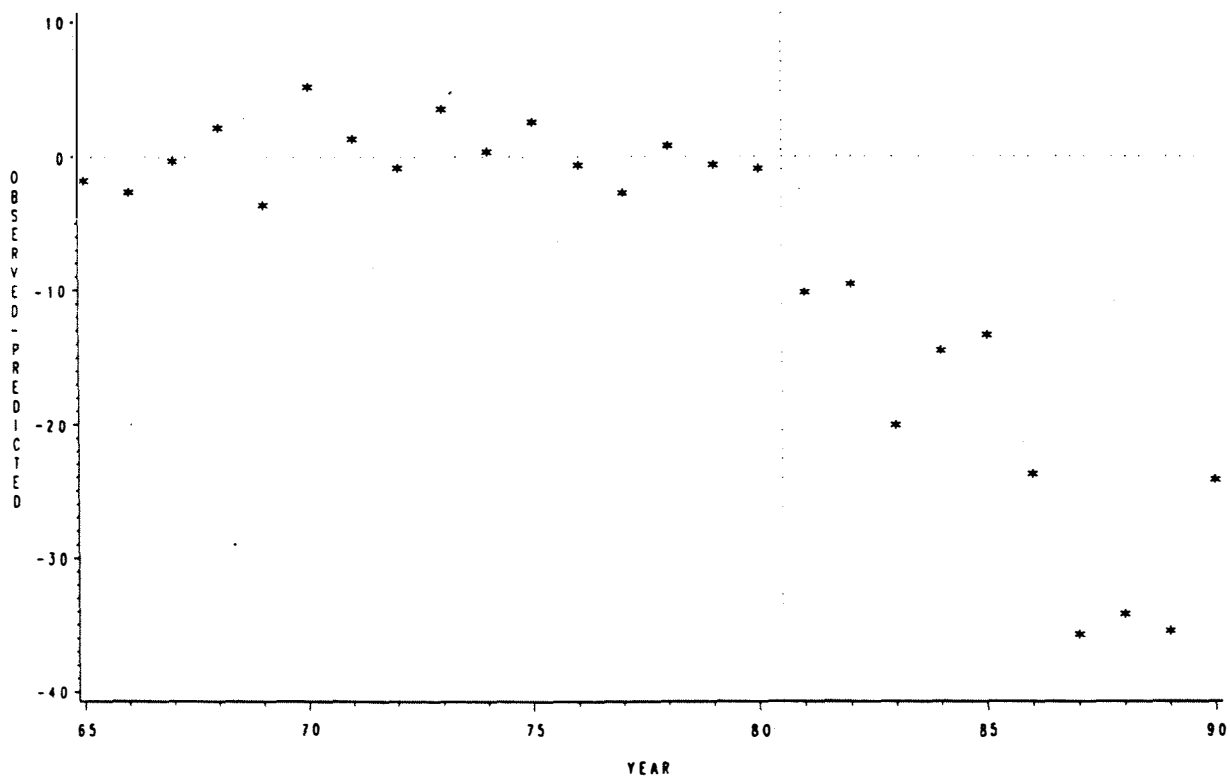


Figure 8. Difference between Observed and Estimated Railway-caused Fire Days, Wawa District. Model was developed using 1965 to 1980 data.

Improvements in lightning fire prediction will have a relatively large impact on the lives of FIO's. New lightning situations and the presence of holdover lightning fires often cause anxiety in regional fire centres.

Ontario's Fire Research and Development Section has identified needs in the area of lightning fire prediction. To encapsulate the larger issues:

1. Is our lightning data collection system the best it can be? We know there are errors in the location quality and detection efficiency of the current lightning location equipment we are using. There are means to improve that information (at a cost) and there are other technologies available.
2. How do we best account for rainfall variability? Precipitation radar technology is available (at a cost). Do we need radar for the resolution of modelling we are doing? Will we be able to use large volumes of precipitation information to our advantage?
3. Are there simple tools and relationships that can assist the FIO to intuitively predict lightning fire occurrences or arrivals? A simple change in the display of lightning to colour-code the strikes to represent fuel moisture can assist the FIO outside of a modelling process. We must continue to support the human decision-maker with information and understanding as we ultimately expect them to analyze the problem.
4. How significant are the meteorological differences between storms to the occurrence of lightning fires? We know that there are differences in the fire potential of certain lightning strikes (long continuing current flashes, for example) (Todd, 1992). Given our current level of understanding and information, we consider all lightning strikes to be similar, regardless of their position relative to the storm track (rainfall), or the nature of the weather system they have evolved from.

Lightning fire occurrence prediction must take advantage of the characteristics of lightning storms that affect fire occurrence. (I call this storm-oriented lightning fire prediction.) Only after we develop a better understanding of the significance of the storm type can we expect to improve the usefulness of lightning activity forecasting. If we understand the significance of certain storm characteristics, presently available weather forecasts may be useful for predicting potential lightning fire problems. These relationships should be pursued before we ask forecasters to predict the presence of lightning or the number of lightning flashes in a storm, which we have seen is difficult (Anderson, 1992). The possibility of certain storm types may be significant information if our understanding of the relative

danger of lightning storms is better understood. For this research, storms might be typed into broad classes related to rainfall patterns, the percentage of long continuing current (LCC) lightning, height to cloud base, etc. We hope that the forest fire community can evaluate the importance of storm characteristics to the prediction of fire occurrence to ultimately make better use of weather forecasts for the prediction of future lightning fire situations.

## CONCLUSIONS

Ontario's experience with operational fire occurrence prediction supports the continued use and development of statistical prediction models. While there are a number of avenues for improvement of people-caused models, the greatest gains can be made in improved understanding of lightning fire processes. Our experience has also confirmed the role of the Fire Intelligence Officer in the interpretation and enhancement of computer generated predictions. The ability of the computer model to quickly summarize large amounts of data will support the FIO's thought process, not replace it, especially where we want to use fire arrival predictions in more advanced decision models.

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- Review of operational weather forecast procedures for the 1984 fire season -- Daniel A. Vandervyvere.
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- Operational lightning fire occurrence prediction in Ontario -- Richard A. White.
- Use of the 500 mb height anomaly chart in fire management -- Ben Janz.
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- A weather network design for forest fire management in Saskatchewan -- R.L. Raddatz.
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- Interpreting the Canadian Forest Fire Weather Index (FWI) System -- William J. De Groot.
- The minisonde as a management tool in planning and conducting a prescribed burn -- Howard G. Wailes.
- Recent developments in the Canadian Forest Fire Danger Rating System -- Robert S. McAlpine and Martin E. Alexander.
- Climatic change: a review of causes -- James B. Harrington.

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- Fire weather/behavior analysis and information systems -- Ugo Feunekes and Ian R. Methven.
- An overview of the 1987 Wallace Lake fire, Manitoba -- Kelvin G. Hirsch.
- Fire behavior on the 1987 Elan fire, Saskatchewan -- William J. DeGroot.
- The fire weather report -- what does it tell us? -- Ben Janz.

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- Atmospheric stability and wind conditions aloft conducive to extreme forest fire behavior -- E.R. Reinelt.
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- Seasonal trends in the drought code component of the Canadian Forest Fire Weather Index System -- R.S. McAlpine.
- Mid-level stability and moisture index: likelihood of extreme fire behavior -- R.L. Raddatz, G. Kluth, and K.G. Hirsch.
- The Intelligent Fire Management Information System: an overview -- K.R. Anderson and B.S. Lee.
- Meteorological and fire behavior characteristics of the 1989 fire season in Manitoba, Canada -- K.G. Hirsch and M.D. Flannigan.

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