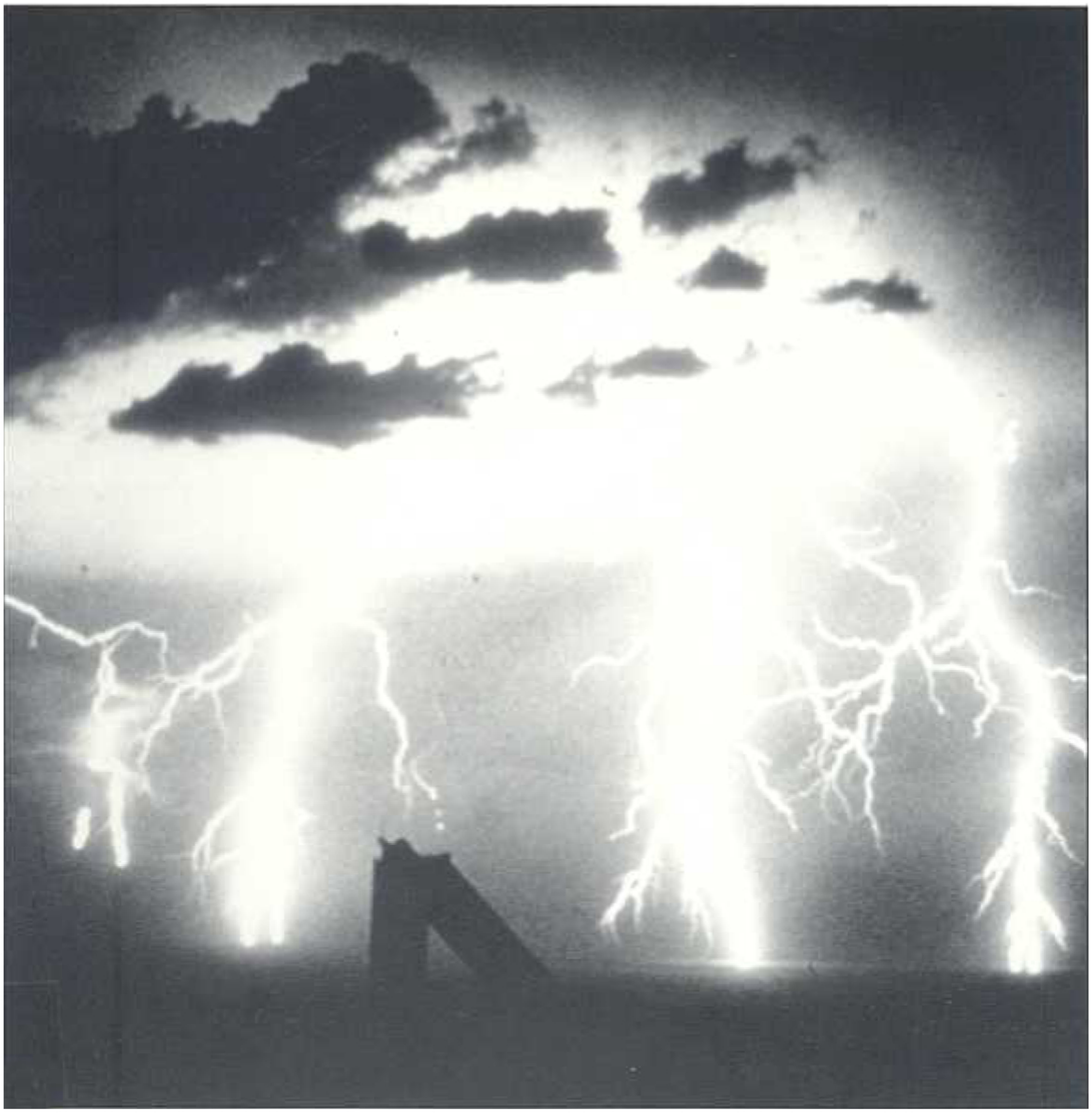
Predicting the Daily Occurence of Lightning-Caused Forest Fires

P. Kourtz and B. Todd
Petawawa National Forestry Insitute • Information Report PI-X-112



Forestry Canada   Forêts Canada

Canada

Predicting the Daily Occurrence of Lightning-Caused Forest Fires

P. Kourtz and B. Todd

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

Catalogue No. Fo46-11/112-1992E
ISBN 0-662-19948-0
ISSN 0706-1854
Printed in Canada

Copies of this publication may be obtained free of charge from the following address:

Forestry Canada
Publications Distribution Centre
Petawawa National Forestry Institute
Chalk River, Ontario
K0J 1J0

Telephone: 613-589-2880

A microfiche edition of this publication may be purchased from:

Micromedia Ltd.
Place du Portage
165, Hôtel-de-Ville
Hull, Québec
J8X 3X2

Cette publication est également disponible en français sous le titre
Prédiction quotidienne des incendies de forêt causés par la foudre.

CANADIAN CATALOGUING IN PUBLICATION DATA

Kourtz, Peter H.

Predicting the daily occurrence of lightning-caused forest fires

(Information report ; PI-X-112)
Includes an abstract in French.
Includes bibliographical references.
ISBN 0-662-19948-0
DSS cat. no. Fo46-11/112-1992E

1. Forest fire forecasting — Canada
2. Forest fires — Canada — Prevention and control.
3. Lightning. I. Todd, B. (James Bernard), 1949-
II. Petawawa National Forestry Institute
III. Title. IV. Series: Information report (Petawawa National Forestry Institute) ; PI-X-112.

SD421.36K68 1992 634.9'615'0971 C92-099765-1

Contents

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 then 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 consument 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 détectibilité. 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 couver 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 couver; 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^2, is partitioned into rectangular geographic units or cells approximately 50 km^2 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^2 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.

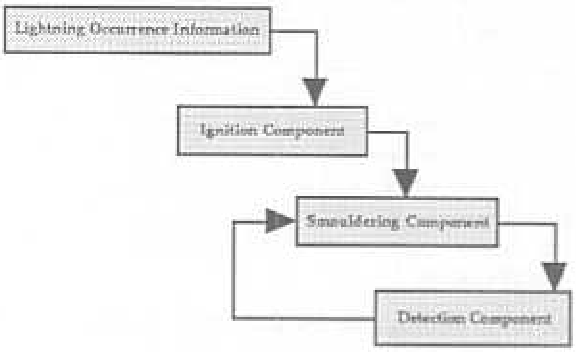


Figure 1. Components of the lightning-caused fire process.

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.

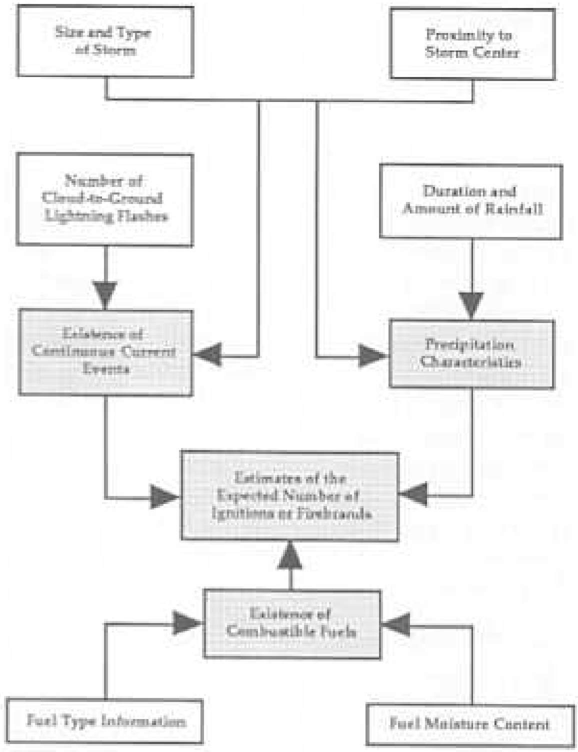


Figure 2. The lightning-caused fire ignition phase.

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 km². 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^2; 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 + [a]	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

[a]Flashes per cell.
Note: Time period, 8 h.

Cell Lightning Flashes

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

Cell Storm Size and Position Classification

51	51	51	51	51	51	51	51
52	52	51	51	51	51	51	51
52	52	51	51	51	51	51	51
52	53	52	51	51	51	53	52
53	53	53	52	51	52	52	53
53	53	53	53	52	52	53	51
54	54	53	52	54	54	53	52
53	54	53	54	54	54	53	53
52	52	52	54	54	54	53	54
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 km², 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[a]

Storm type		Storm center (4)	Near storm center (3)	Near storm edge (2)	Storm edge (1)
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

[a]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]).

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

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 FFMC, wind speed, temperature, and relative humidity determine whether or not fires will be detectable. At one extreme, on hot, dry, windy days with high FFMC 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.

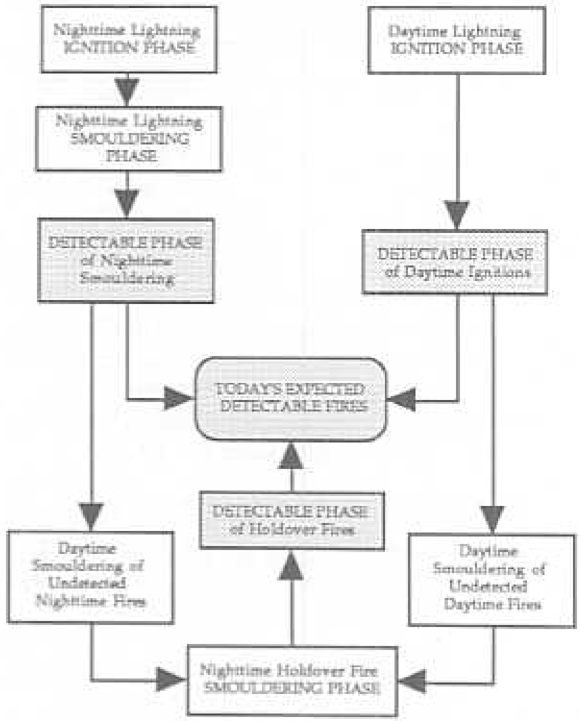


Figure 4. Elements of the detectable phase of lightning-caused fires.

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 km² 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 km² 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^2 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.

References

Baughman, R.G.; Schmid, C.W. 1977. Alaskan lightning storm characteristics. USDA For. Serv. Res. Note, INT-235, Intermt. For. and Range Exp. Stn., Ogden, UT.

Bellaschi, P.L. 1947. Lightning and 60-cycle power tests on wood-pole line insulation. AIEE Trans. 66:838-847.

Flannigan, M.D.; Wotton, B.M. 1991. Lightning-ignited forest fires in northwestern Ontario. Can. J. For. Res. 21:277-287.

Fosberg, M.A. 1972. Theory of precipitation effects on dead cylindrical fuels. For. Sci. 18:98-108.

Fuquay, D.M. 1980. Lightning that ignites forest fires. Proc. 6th Conf. on Fire and For. Met., Seattle, WA, 109-112.

Fuquay, D.M.; Baughman, R.G.; Taylor, A.R.; Hawe, R.G. 1967. Documentation of lightning discharges and resultant forest fires. USDA For. Serv. Res. Note, INT-68, Intermt. For. and Range Exp. Stn., Ogden, UT.

Fuquay, D.M.; Baughman, R.G.; Latham, D.J. 1979. A model for predicting lightning fire ignition in wildland fuels. USDA For. Serv. Res. Pap., INT-217, Intermt. For. and Range Exp. Stn., Ogden, UT.

Kitagawa, N.; Brook, M.; Workman, E.J. 1962. Continuing currents in cloud-to-ground lightning discharges. J. Geophys. Res. 67:637-647.

Kourtz, P.H. 1974. A system to predict the occurrence of lightning-caused forest fires. For. Fire Res. Inst., Ottawa, Ont., Inf. Rep. FF-X-47.

Kourtz, P.H. 1977. Structure of the 1977 forest fire occurrence prediction model. For. Fire Res. Inst., Ottawa, Ont.

Kourtz, P.H. 1984. Decision-making for centralized forest fire management. For. Chron. 60:320-327.

Latham, D.L. 1980. A channel model for long arcs in air. Phys. Fluids 23:1710-1715.

Latham, D.L. 1989. Characteristics of long vertical DC arc discharges. USDA For. Serv. Res. Note, INT-407, Intermt. For. and Range Exp. Stn., Ogden, UT.

Latham, D.L.; Schlieter, J.A. 1989. Ignition probabilities of wildland fuels based on simulated lightning discharges. USDA For. Serv. Res. Note, INT-411, Intermt. For. and Range Exp. Stn., Ogden, UT.

Levin, Z.; Ziv, A. 1974. The electrification of thunderclouds and the rain gush. J. Geophys. Res. 79:2699-2704.

Marshall, J.S.; Radhakant, S. 1978. Radar precipitation maps as lightning indicators. J. Appl. Meteorol. 17:206-212.

Noggle, R.C.; Krider, E.P.; Vance, D.L.; Barker, K.B. 1976. A lightning-direction-finding system for forest fire detection. Proc. 4th Natl. Conf. on Fire and Met., St. Louis, MO.

Orville, R.E. 1972. Lightning between clouds and ground. Weatherwise (June):108-111.

Orville, R.E. 1990. Peak-current variations of lightning return strokes as a function of latitude. Nature 343:149-151.

Piepgrass, M.V.; Krider, E.P.; Moore, C.B. 1982. Lightning and surface rainfall during Florida thunderstorms. Geophys. Res. Pap. 87:11193-11201.

Ramsey, G.S.; Higgins, D.G. 1986. Canadian forest fire statistics 1981, 1982, 1983. Petawawa Natl. For. Inst., Inf. Rep. PI-X-49 E/F.

Shindo, T.; Uman, M.A. 1989. Continuing current in negative cloud-to-ground lightning. J. Geophys. Res. 94:5189-5198.

Taylor, A.R. 1969. Lightning effects on the forest complex. Annual Tall Timbers Fire Ecol. Conf. Proc., Tallahassee, FL, 9:127-150.

Uman, M.A.; Krider, E.P. 1989. Natural and artificially initiated lightning. Science 246:457-464.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., Petawawa Natl. For. Inst., For. Tech. Rep. 35.

Wilson, C.T.R. 1916. Proc. R. Soc. London A92:555.

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

Quebec fuel type	Latham and Schlieter fuel type			
Softwood				
Regeneration	Peat moss			
Young	Pine litter			
White pine	Pine duff			
Other pines with intolerant hardwood	Pine duff			
Mature stands	Pine duff			
Mixedwood				
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			
Hardwood				
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[a]
		Daytime ignition fires		
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
		Nighttime ignition fires		
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[a]
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
		Holdover fires		
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

[a] Refer to Table 6 for actual equation.