LIGHTNING-CAUSED FIRE OCCURRENCES: AN OVERVIEW[1]

by Kerry Anderson[2]

ABSTRACT

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

INTRODUCTION

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

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

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THE PHYSICAL PROCESS

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

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

Ignition

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$Q_M = \int_{T_{amb}}^{100°C} c_{p_w} dT + l_v \qquad (6)$$

$$\approx 4.18(100 - T_{amb} + 540) \quad [kJ/kg]$$

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

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

Lightning

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Survival

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

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

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

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

Arrival

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

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

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

THE FUQUAY MODEL

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

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

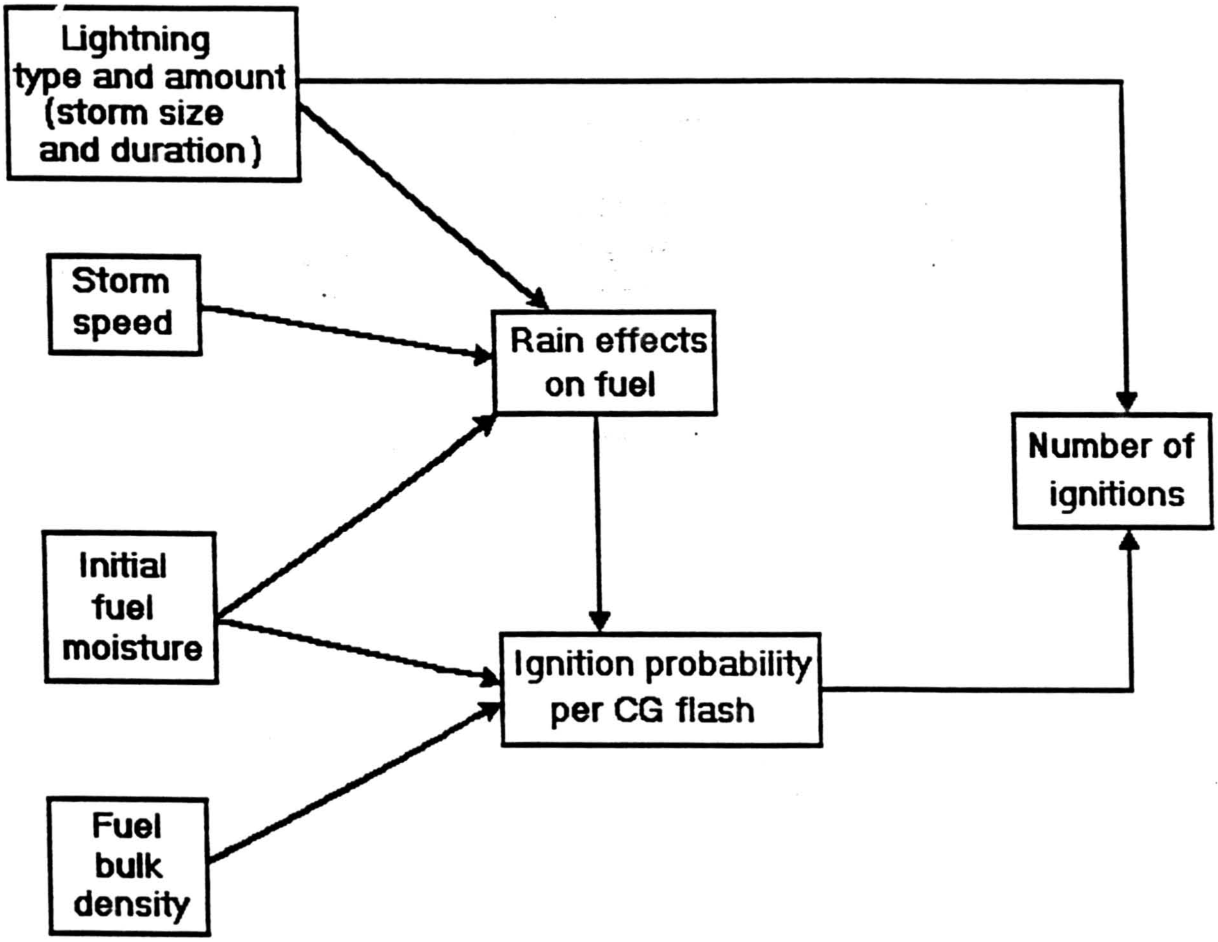

Figure 1. Fuquay's model of the lightning ignition fire environment (adapted from Fuquay *et al.* 1979).

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

Inputs

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

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

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

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

Intermediate Values

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

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

Output

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

PROGRESS

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

Ignition

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

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

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

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

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

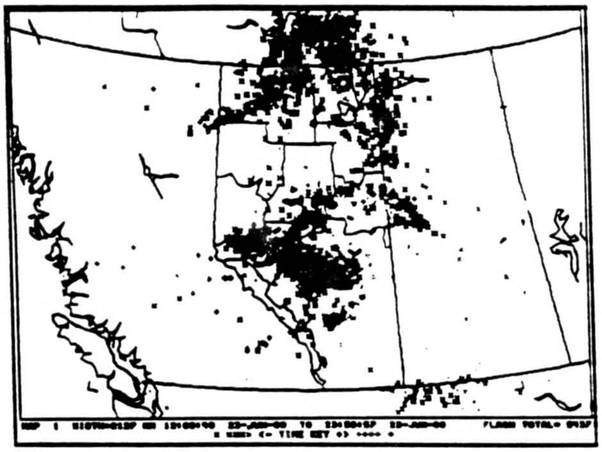

Figure 2. Lightning detection map for June 23, 1988.

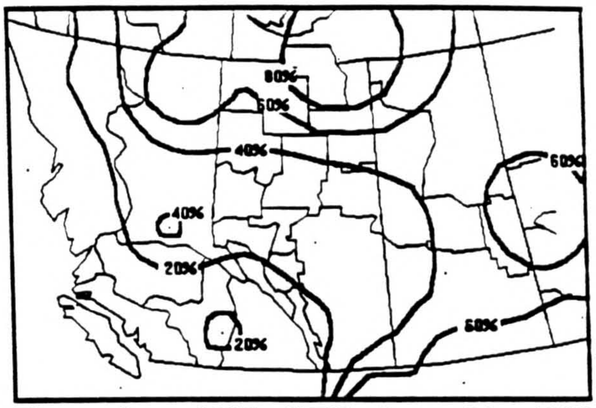

Figure 3. 0000 UTC June 24, 1988 negative lightning occurrence prediction map.

Long continuing currents

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

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

Ignition probabilities

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

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

Survival

Smouldering fires

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

$$SMI = DC\ e^{\frac{-300}{DMC^2}} \qquad (9)$$

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

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

Arrival

Fire behavior

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

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

Fire extinction

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

DISCUSSION

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

LIST OF SYMBOLS

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

BIBLIOGRAPHY

Anderson, K.R. 1991. Models to predict lightning occurrence and frequency over Alberta. M.Sc. thesis. University of Alberta. 91 pp.

Anderson, K.R.; Charlton, R.B. 1990. Predicting lightning occurrence and frequency from upper air soundings over Stony Plain, Alberta. Pages J40-J45 in 16th Conf. on Severe Local Storms/Conf. on Atmospheric Electricity. Oct. 22-24, 1990. Kananaskis Prov. Park, Alberta. AMS, Boston.

Andersson, T; Andersson, A.; Jacobsson, C.; Nilsson, S. 1989. Thermodynamic indices for forecasting thunderstorms in southern Sweden. Meteo. Mag. 118:141-146.

Barrows, J.S. 1951. Forest fires in the northern Rocky Mountains. Sta. Pap. 28. USDA For. Serv., N. Rocky Mountain Forest and Range Exp. Sta., Missoula, MT. 251 pp.

Bent, R.B.; Lyons, W.A. 1984. Theoretical evaluations and initial operational experiences of LPATS (Lightning Position And Tracking System) to monitor lightning ground strikes using a time-of-arrival (TOA) technique. Pages 317-324 in 7th Intl. Conf. on Atmospheric Electricity. June 3-8, 1984. Albany, N.Y. AMS, Boston.

Chalmers, J.A. 1967. Atmospheric electricity. Pergamon press, New York, NY. 515 pp.

Chrosciewicz, Z. 1989. Prediction of forest-floor moisture content under diverse jack pine canopy conditions. Can. J. For. Res. 19(11): 1483-1487.

Deeming, J.E.; Lancaster, J.W.; Fosberg, M.A.; Furman, R.W.; Schroeder, M.J. 1972. National fire danger rating system. USDA For. Serv. Res. Pap. RM-84. Rocky Mt. For. and Range Exp. Stn., Ft. Collins, CO. 165 pp.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Inf. Rep ST-X-3. Forestry Canada, Science and Sustainable Development Directorate, Ottawa, ON. 63 pp.

Flannigan, M.D.; Watton, B.M. 1990. 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.

Frandsen, W.H. 1973. Effective heating of fuel ahead of spreading fire. USDA For. Serv. Res. Pap. INT-140. Intermt. For. and Range Exp. Stn., Ogden, UT. 16 pp.

Frandsen, W.H. 1987. The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. Can. J. For. Res. 17: 1540-1544.

Fuquay, D.M. 1980. Forecasting lightning activity level and associated weather. USDA For. Serv. Res. Pap. INT-244. Intermt. For. and Range Exp. Stn., Ogden, UT. 30 pp.

Fuquay, D.M.; Baughman, R.G.; Taylor, A.R.; Hawe, R.G. 1967. Characteristics of seven lightning discharges that caused forest fires. J. Geophys. Res. 72(24): 6371-6373.

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. 21 pp.

Fuquay, D.M.; Taylor, A.R.; Hawe, R.G.; Schmid, C.W. Jr. 1972. Lightning discharges that caused forest fires. J. Geophys. Res. 77(12): 2156-2158.

Golde, R.H. 1977. Lightning: volume 1, physics of lightning. Academic Press, London. 496 pp.

Hartford, R.A. 1990. Smoldering combustion limits in peat as influenced by moisture, mineral content, and organic bulk density. Pages 282-286 in Proc. 10th Conf. on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada. AES, Downsview, Ont.

Hirsch, K.G. 1991. A chronological overview of the 1989 fire season in Manitoba. For. Chron. 67(4): 358-365.

Kourtz, P.H. 1967. Lightning behaviour and lightning fires in Canadian forests. For. Branch pub. no. 1179-1967. Dept. For. and Rural Dev., Ottawa, Ont. 33 pp.

Kourtz, P.H. 1974. A system to predict the occurrence of lightning-caused forest fires. Can. For. Serv. Inf. Rep. FF-X-47. For. Fire Res. Inst., Ottawa, Ont. 17 pp.

Kourtz, P.H.; Todd, B. 1992. Predicting the daily occurrence of lightning-caused forest fires. In preparation. Petawawa Natl. For. Inst., Chalk River, ON.

Krider, E.P.; Noggle, R.C.; Pifer, A.E.; Vance, D.L. 1980. Lightning direction-finding systems for forest fire detection. Bull. Amer. Meteo. Soc. 61:980-986.

Krider, E.P.; Noggle, R.C.; Uman, M.A. 1976. A gated, wideband magnetic direction finder for lightning return strokes. J. Appl. Meteo. 15:301-306.

Latham, D.J. 1983. LLAFFS - a lightning locating and fire-forecasting system. USDA For. Serv. Res. Pap. INT-315. Intermt. For. and Range Exp. Stn., Ogden, UT. 44 pp.

Latham, D.J. 1979. Progress towards locating lightning fires. USDA For. Serv. Res. Note INT-269. Intermt. For. and Range Exp. Stn., Ogden, UT. 6 pp.

Latham, D.J.; Schlieter, J.A. 1989. Ignition probabilities of wildland fuels based on simulated lightning discharges. USDA For. Serv. Res. Pap. INT-411. Intermt. For. and Range Exp. Stn., Ogden, UT. 16 pp.

Mach, D.M.; MacGorman, D..R.; Rust, W.D. 1986. Site errors and detection efficiency in a magnetic direction-finder network for locating lightning strikes to ground. J. Atm. and Oceanic Tech. 3:67-74.

Nimchuk, N. 1983. Wild fire behavior associated with upper ridge breakdown. ENR Rep. No. T/50. Alberta Energy and Nat. Res., Edmonton, Alta. 46 pp.

Nimchuk, N. 1989. Ground truthing the LLP lightning data in Alberta. Pg 33-40 in Proc. 10th Conf. Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada. AES, Downsview, Ont.

Ogilvie, C.J. 1989. Lightning fires in Saskatchewan forests. Can. For. Serv. Fire Man. Notes 50(1):31-32.

Orville, R.E. 1991. Calibration of a magnetic direction finding network using measured triggered lightning return stroke peak currents. J. Geophys. Res. 96(D9):17,135-17,142.

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

Reap, R.M. 1990. Thunderstorms over Alaska as revealed by lightning location data. Pages J46-J51 in 16th Conf. on Severe Local Storms/Conf. on Atmospheric Electricity. Oct. 22-24, 1990. Kananaskis Prov. Park, Alberta. AMS, Boston.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Pap. INT-115. Intermt. For. and Range Exp. Stn., Ogden, UT. 40 pp.

Shindo, T.; Uman, M.A. 1989. Continuing current in negative cloud-to-ground lightning. J. Geophys. Res. 94(D4): 5189-5198.

Susott, R.A. 1982a. Characterization of the thermal properties of forest fuels by combustible gas analysis. Forest Sci. 28(2):404-420.

Sussot, R.A. 1982b. Diferential scanning calorimetry of forest fuels. Forest Sci. 28(4):839-851.

Taylor, A.R. 1964. Lightning damage to forest trees in Montana. Weatherwise 17(2): 61-65.

Tithecott, A.G. 1991. Lightning-caused forest fire arrival model verification. Internal document. Research and development section, AFMC, OMNR, Sault St. Marie, Ont. 7 pp.

Uman, M.A. 1969. Lightning. McGraw Hill, New York, NY. 264 pp.

Uman, M.A. 1987. The lightning discharge. Academic Press, Orlando, FL. 377 pp.

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

Wilson, R.A. 1985. Observation of extinction and marginal burning states in free burning porous fuel beds. Combust. Sci. and Tech. 44:179-193

Wilson, R.A. 1990. Reexamination of Rothermel's fire spread equations in no-wind and no-slope conditions. USDA For. Serv. Res. Pap. INT-434. Intermt. For. and Range Exp. Stn., Ogden, UT. 13 pp.

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