Lightning-ignited forest fires in northwestern Ontario

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This study investigates the relationship between lightning activity and the occurrence of lightning-ignited forest fires in the Northwestern Region of Ontario. We found that the Duff Moisture Code (a component of the Fire Weather Index System) and the multiplicity of the negative lightning discharges were the most important variables for estimating the number of lightning-ignited fires on a daily basis for Universal Transverse Mercator zone 15 in Ontario. Also, the results indicate that negative lightning ignited more fires than positive lightning discharges, which is contrary to popular belief. Nearly 50% of the variance in the forest fire occurrence data was explained using linear stepwise regression. Future work will focus on finer temporal and spatial scales.

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L'article traite la relation entre les éclaires et les incendies de forêt qui en sont résultés. D'après nos études, l'indice de l'humus (qui fait partie de l'Indice forêt-météo) et la multiplication de déchargement négatif des éclaires étaient les variables les plus importantes lors de l'estimation du nombre de tels incendies. L'évaluation a déroulé quotidiennement en Ontario, dans la zone 15 de Projection transversale universelle de Mercator. Selon nos observations, les éclaires de déchargement négatif causaient plus d'incendies que ceux du déchargement positif, ce qui est le contraire de l'opinion répandue dans le public. Presque 50% des variations des données sur les incendies de forêt ont été expliquées en suivant une méthode de régression linéaire. Dans les travaux futurs, des échelles plus petites seront utilisées quant aux mesures du temps ou de références géographiques.

Introduction

Wildfires ignited by lightning have always been a part of the natural environment of Canadian forests. In Ontario, lightning has ignited 664 forest fires per year, as averaged over the 10-year period 1979–1988. These fires have been responsible for 70% of the burned area (198 436 ha per year) for the same 10-year period. Each year, millions of dollars are spent on the suppression of these fires in Ontario. Lightning fires are often more difficult to suppress than human-caused fires because lightning fires are more likely to start in remote areas. Because of the remoteness of these fires, the helicopter has become the only viable means of transporting men and equipment to the fire. When ignition is remote, more time is required to detect and reach the fire, thereby allowing the fire time to grow; of course, the larger the fire the more difficult it is to extinguish. Given the appropriate weather and fuel conditions, lightning-ignited wildfires also have a tendency to occur as multiple occurrences, with consequent severe strain on the fire management agencies.

The study of lightning behaviour related to forest fires is not new (Fuquay et al. 1967; Kourtz 1967). Models have been developed for predicting lightning fire ignition of wildland fuels (Fuquay et al. 1979; Kourtz 1974). The present work is a preliminary diagnostic investigation aimed at providing a predictive model to fire management agencies for advance warning of potential lightning-ignited wildfires.

The majority of lightning fires occur in the Northwestern Region of Ontario, and we shall focus on this area (Fig. 1). Ignition of forest fuels is dependent on many factors, including the following: (*i*) type, density, and depth of fuel struck by lightning; (*ii*) fuel moisture; (*iii*) ventilation; and (*iv*) characteristics of the lightning discharge (duration). Research (Fuquay et al. 1967, 1972, 1979) has shown that the long-continuing current (LCC) phase of a lightning discharge is responsible for most, if not all, lightning-caused fires. Conversely, not every LCC will ignite a fire and not every discharge contains a LCC phase. A great amount of uncertainty exists when working with lightning because location and path of the lightning discharge are somewhat random.

The purpose of this study is to explore the relationships between the occurrence of lightning-ignited wildfires and lightning activity, fuel, and weather conditions. In particular, this study will address the relationship between the occurrence of lightning-ignited wildfires and the frequency and characteristics of lightning discharges, including charge (position or negative), number of return strokes, and normalized strength. The impact of fuel moisture on the occurrence of lightning-induced wildfire will also be studied. The impact of weather, particularly precipitation amount and pattern in tandem with lightning activity, will be examined in regards to wildfires started by lightning.

Data

The Ontario Ministry of Natural Resources (OMNR) operates a lightning location system using equipment developed by Lightning Location and Protection Inc., Tucson, Arizona. This lightning location system uses electromagnetic frequencies in the 1 kHz to 1 MHz range to detect cloud to ground lightning discharges. The polarity of the electromagnetic signal is detected by an electric field antenna, while the azimuth angle is determined using a cross-loop magnetic field antenna. The incoming electromagnetic signal is compared with known lightning signature profiles. If the signal is determined to be a cloud to ground lightning discharge, then information on the lightning discharge is recorded. When two or more sites detect a lightning discharge, a central computer triangulates the location of the lightning event. Presently, the OMNR operates a network of 12 direction finders (antenna sites) across the province of Ontario and has access to four direction finders in southern Ontario operated by Ontario Hydro and the

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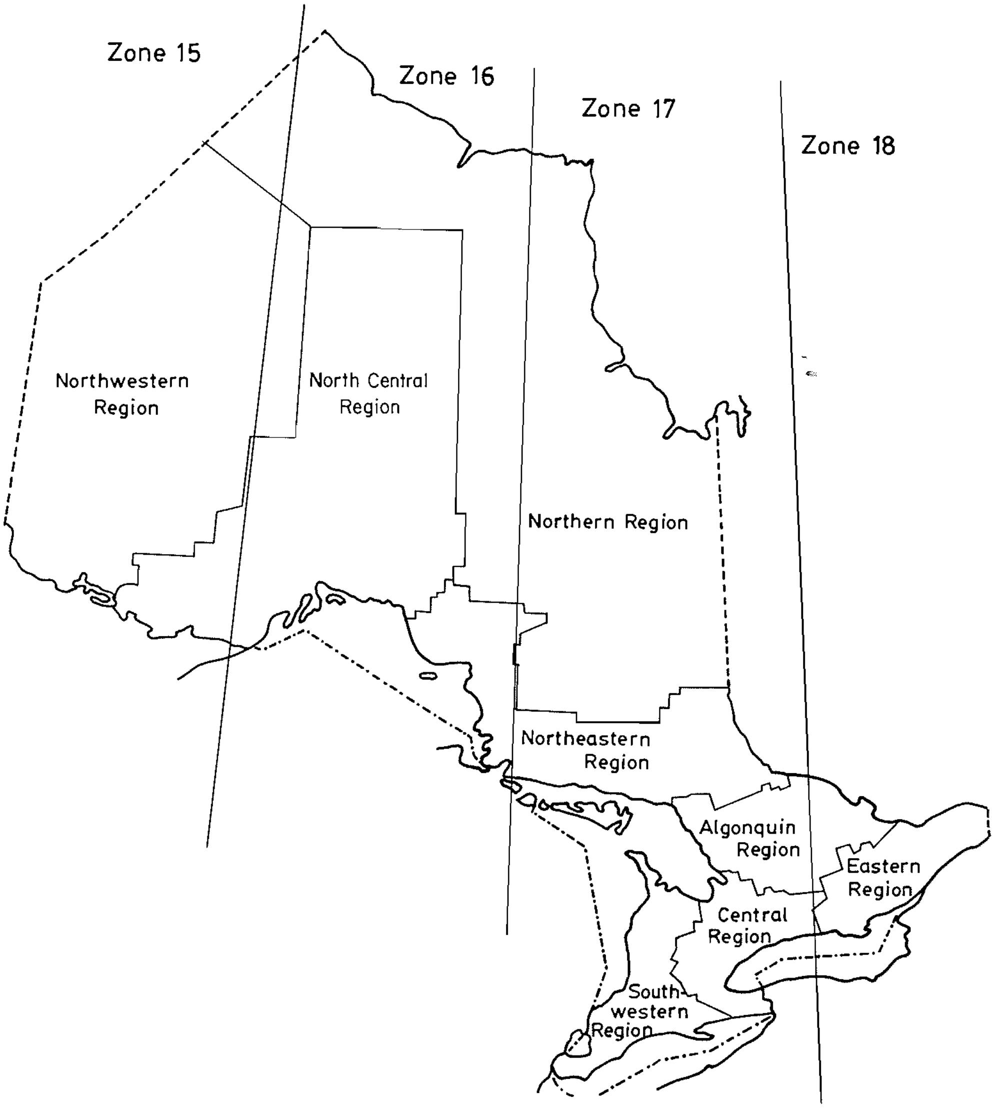

FIG. 1. Province of Ontario with UTM zones.

TABLE 1. Number of reported lightning-ignited forest fires by UTM zone and month in 1988

UTM zone*	April	May	June	July	August	September	Season
15	0	169	597	232	146	8	1152
16	0	21	103	89	20	0	233
17	0	9	235	190	80	2	516
18	0	4	10	20	36	0	70
All Ontario	0	203	945	531	232	10	1971

*Please see Fig. 1 for location of zones.

Canadian Atmospheric Environment Service. Additional information on the principles of operation for this type of lightning location network can be found in Krider et al. (1980).

For the purpose of this study, 1988 lightning data were obtained from the OMNR. The data consist of the date and time of the cloud to ground lightning discharge, an identification number (numbered sequentially), the location (latitude and longitude), the polarity of the discharge (positive or negative[1]), normalized signal strength (normalized to a distance of 100 km), and the multiplicity, which is the number of return strokes for each lightning discharge. Unfortunately, lightning location equipment does not detect LCCs in the lightning discharge. Between 50 and 100% of all positive-charged discharges have a LCC component (Beasley et al. 1983; Brook et al. 1982; Fuquay 1982; Rust et al. 1981; Tukeuti et al. 1978), while one-quarter to one-half of negative discharges have a LCC component (Uman and Krider 1989).

Weather data for 1988 (Northwestern and North Central regions), were also obtained from the OMNR. The OMNR operates a fire weather network with over 100 weather stations across the

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[1] Positive flashes lower positive charge to earth, conversely negative flashes lower negative charge to earth.

TABLE 2. Summary of lightning data for UTM zone 15 and the province of Ontario, April 15 - September 21, 1988

	UTM zone 15*			Province of Ontario		
	No. of discharges	% positive	% negative	No. of discharges	% positive	% negative
Month						
Apr.	0	0	0	7	14.3	85.7
May	18 408	4.0	96.0	49 595	5.7	94.3
June	45 434	5.7	94.3	127 441	4.5	95.5
July	67 846	7.1	92.9	184 635	4.7	95.3
Aug.	26 673	8.9	91.1	142 775	4.6	95.4
Sept.	10 728	12.0	88.0	51 684	6.4	93.6
Season	169 089	7.0	93.0	556 137	4.9	95.1
Hour						
00-01	7 439	9.2	90.8	22 816	5.3	94.7
01-02	6 806	8.6	91.4	20 504	5.6	94.4
02-03	6 640	10.6	89.4	17 907	6.4	93.6
03-04	6 998	11.0	89.0	16 689	7.5	92.5
04-05	7 279	13.2	86.8	18 346	9.0	91.0
05-06	7 638	10.0	90.0	16 930	8.1	91.9
06-07	6 761	9.8	90.2	16 449	7.5	92.5
07-08	5 146	8.7	91.3	13 440	7.0	93.0
08-09	4 426	7.4	92.6	12 240	7.1	92.9
09-10	3 426	7.2	92.8	10 941	7.4	92.6
10-11	1 537	9.8	90.2	7 127	9.3	90.7
11-12	2 842	5.2	94.8	9 567	7.7	92.3
12-13	2 130	5.4	94.6	11 918	4.6	95.4
13-14	3 880	2.2	97.8	18 579	3.3	96.7
14-15	5 181	2.7	97.3	24 491	3.3	96.7
15-16	6 113	5.2	94.8	29 822	3.5	96.5
16-17	7 740	4.0	96.0	38 348	3.0	97.0
17-18	9 862	3.5	96.5	42 284	3.1	96.9
18-19	11 743	3.9	96.1	40 819	3.5	96.5
19-20	12 353	4.6	95.4	37 736	3.8	96.2
20-21	11 486	6.5	93.5	34 590	4.3	95.7
21-22	11 792	6.5	93.5	35 898	4.2	95.8
22-23	10 588	6.8	93.2	32 083	4.5	95.5
23-24	9 283	8.5	91.5	26 613	5.3	94.7

*Data are for UTM zone 15 up to and including northing 585.

province of Ontario (all are manually observed except three automatic stations). The weather data include temperature, relative humidity, wind speed, and the 24-h precipitation, all recorded at 12:00 local standard time (13:00 local daylight saving time).

Information on wildfire occurrence also came from the OMNR. Wildfire data include location (Universal Transverse Mercator (UTM) coordinates, i.e., zone, easting, northing), fire identification number, cause of fire, discovery date and time, size at discovery, and estimated day of ignition.

Varying degrees of uncertainty are associated with the data sets. Lightning detection efficiencies are probably around 70% (Gilbert et al. 1987; Mach et al. 1986), but this is a function of the density of the network direction finders. Accuracy of the triangulated location is dependent on the distance from the direction finder to the lightning discharge as well as on problems related to the direction finder site, such as distortion or blocking of the electromagnetic signal by the local terrain. In Alberta, Nimchuk (1989) found errors of 3–10 km in the location of lightning position, depending on the density of direction finders. Errors of 3–10 km are also probable for the Ontario network of direction finders. Weather data also have some uncertainties. First, the information is recorded only once a day, and second, the representativeness of the observation decreases with distance from the weather station. As well, the data are only as good as the equipment and observers recording the observation. Fire report data also contain uncertainties because the date of ignition can be difficult to ascertain.

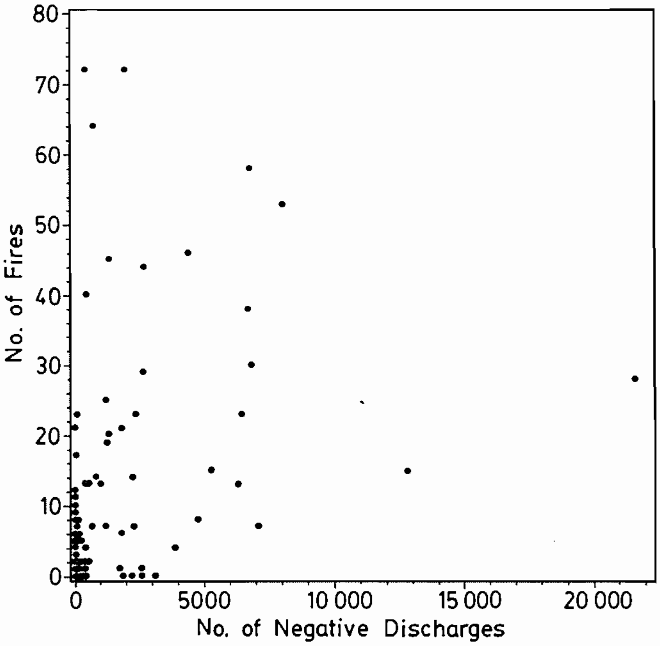

FIG. 2. Reported lightning fires versus the number of negative lightning discharges on a daily basis.

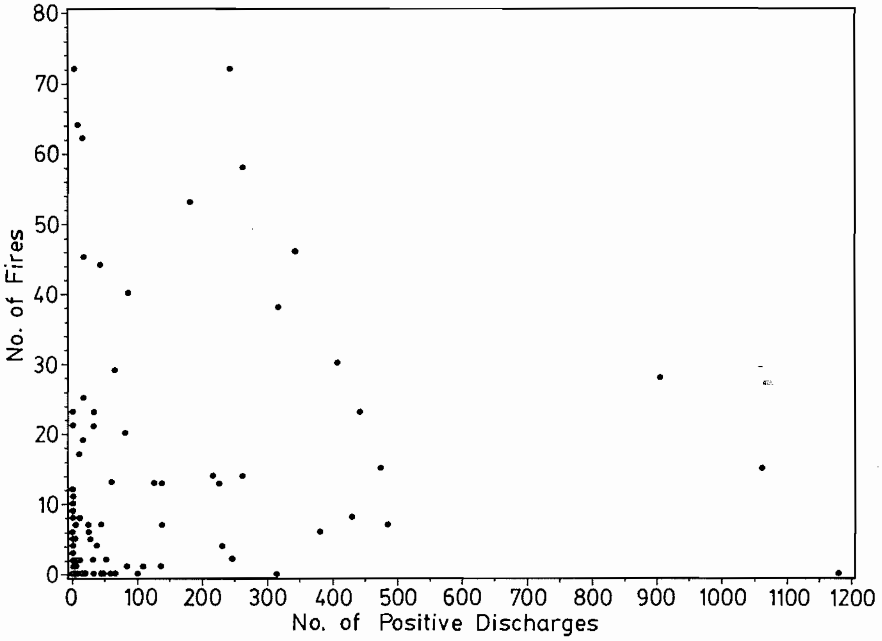

FIG. 3. Reported lightning fires versus the number of positive lightning discharges on a daily basis.

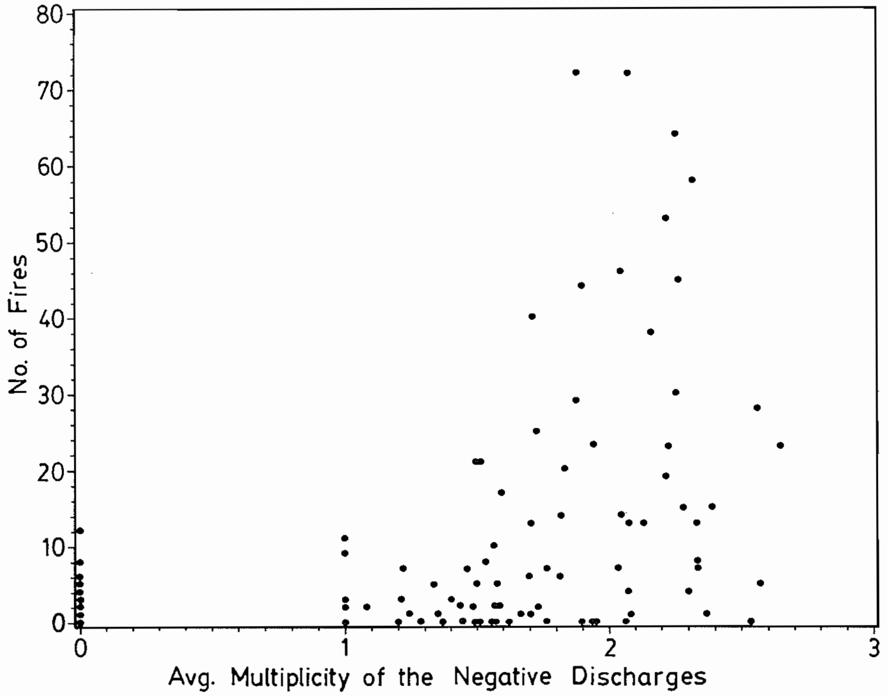

FIG. 4. Reported lightning fires versus the average multiplicity of negative lightning discharges.

Method

The first step was to standardize the spatial coordinate system. All the lightning data that were archived with location described by longitude and latitude were transformed to UTM to be consistent with the fire data.

Next, lightning frequency was studied to observe seasonal, diurnal, and geographical trends, including the distribution of positive and negative lightning discharges. In this study, 1988 was the only year studied; however, as more data become available, the confidence in the statistics generated will increase.

A linear regression model was used to determine the number of lightning-caused fire starts per day on a UTM zone basis using only the lightning information. Only UTM zone 15 (Fig. 1) was used in the regressions, because this zone had over 50% of the lightning fires in Ontario in 1988. A second regression model used the lightning and weather data as well as the components of the Canadian Forest Fire Weather Index System[2] to explain the variance in the lightning-ignited forest fires. The components of the FWI system were calculated from the weather data by equations outlined by Van Wagner (1987).

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[2] The Fire Weather Index system comprises three fuel moisture codes and three fire behaviour indexes. The three moisture codes represent the moisture content of fine fuels (Fine Fuel Moisture Code), loosely compacted decomposing organic matter (Duff Moisture Code), and the deep layer of compact organic matter (Drought Code). The three fire behaviour indexes, which are derived from the moisture codes and the surface wind, indicate the rate of initial fire spread (Initial Spread Index), total available fuel (Build Up Index), and the intensity of spreading fire (Fire Weather Index).

TABLE 3. Explained variances and variables selected by stepwise regression for UTM zone 15 in Ontario

Step	Variable entered*	Partial R^2	Model R^2
1	MN	0.24	0.24
2	SN	0.06	0.30
3	ND	0.02	0.32
4	PDM	0.05	0.37
5	PD	0.06	0.43
All 8 variables			0.43

*MN, average multiplicity of negative discharges; SN, average strength of the negative discharges; ND, number of negative discharges; PDM, number of positive discharges × average multiplicity of positive discharges; PD, number of positive discharges.

TABLE 4. Explained variance and variables selected by stepwise regression for UTM zone 15 in Ontario

Step	Variable entered*	Partial R^2	Model R^2
1	DMC	0.25	0.25
2	MN	0.15	0.40
3	ND	0.04	0.44
4	Wind speed	0.02	0.47
All variables			0.62

*DMC, Duff Moisture Code; MN, average multiplicity of negative discharges; ND, number of negative discharges.

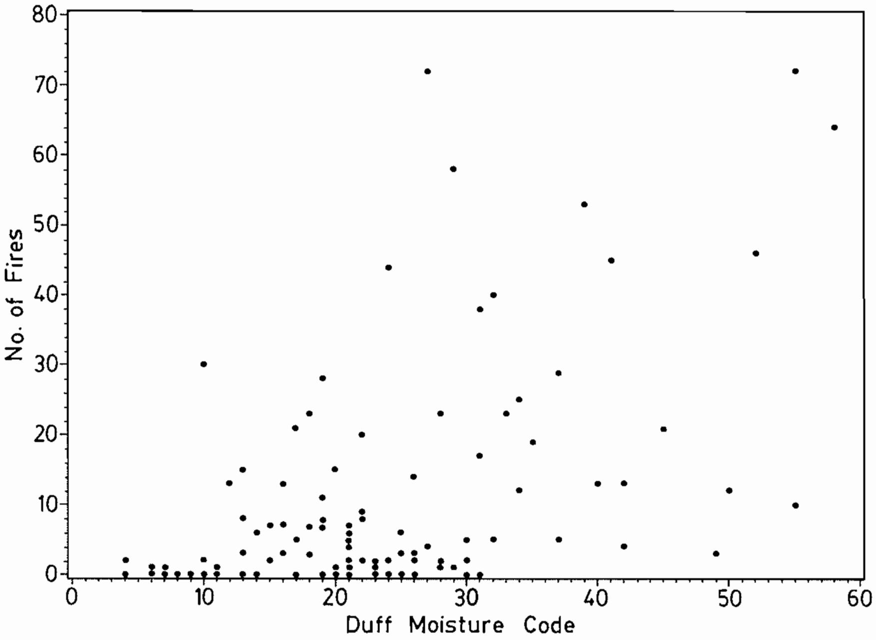

FIG. 5. Reported lightning fires versus the Duff Moisture Code.

An important aspect of the study was a detailed inspection during a number of specific days. This included days with significant lightning activity and a large number of lightning fire starts, days with significant lightning activity and a small number (if any) of lightning fire starts, and finally, days with limited lightning activity but a large number of fire starts. The lightning and fire occurrence data were plotted together to investigate any structure or relationship. Finally, the other data were superimposed on lightning and fire data.

Results and discussion

Lightning-ignited forest fire statistics for 1988 for UTM zones 15–18 and for the province are shown in Table 1. In 1988, forest fire occurrence showed a seasonal trend of activity with no fires in April, rising in May to a maximum in June, and then declining slowly in July and August, with a sharp fall in September. Table 2 shows lightning summary statistics for UTM zone 15 and for the province of Ontario for April 15 - September 21, 1988. During this period over 500 000 lightning discharges were observed in Ontario. Of the total, 95% were negatively charged while only 5% were positively charged. This ratio of negative to positive discharges is consistent with other studies (Uman 1987). The rationale for discriminating between positive and negative discharges is that positive discharges have a significantly higher probability of having a LCC phase compared with negative discharges and, hence, a greater ignition potential. Lightning activity shows a seasonal trend with a little activity in May, rising through June to a maximum in July, declining slightly in August, then falling sharply in September. The percentage of positive lightning discharges also shows a seasonal trend with a minimum in May or June rising to a maximum by September. On a diurnal basis, lightning activity is at a maximum in the evening and at a minimum during midmorning. Diurnal and seasonal trends of lightning activity in this study are in general agreement with those of other studies (Reap and Orville 1990).

The seasonal trends of the lightning occurrence data (Table 2) and the lightning-ignited forest fire data are out of phase. Fire ignitions are higher in May and June, especially in UTM zone 15, than one would expect from the lightning frequency data. Additional years will have to be analyzed to verify if the trend in 1988 is representative. Typically in this region, there is a potential for a large number of ignitions every spring. This can happen during a 2- to 4-week period after the snow has melted but prior to forest vegetation flush. The forest floor at this time is covered by dead,

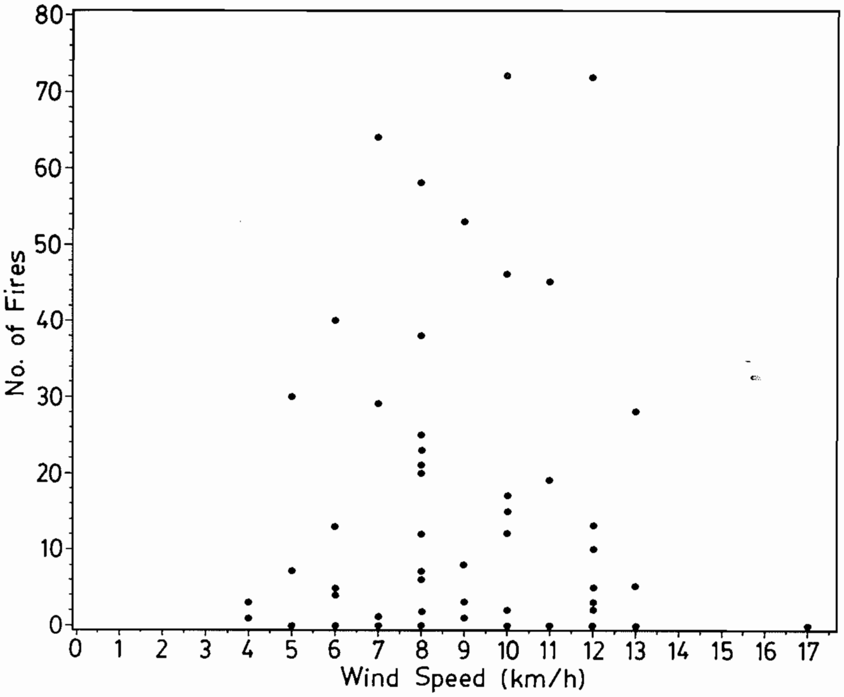

FIG. 6. Reported lightning fires versus wind speed.

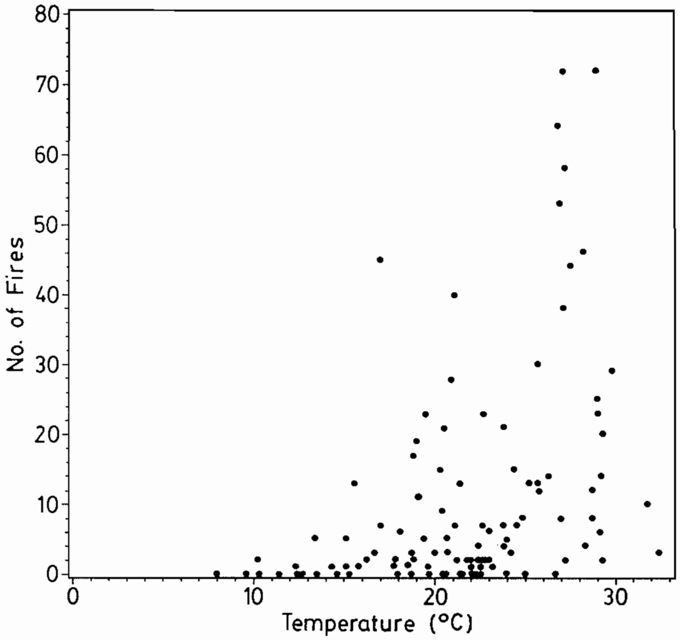

FIG. 7. Reported lightning fires versus temperature.

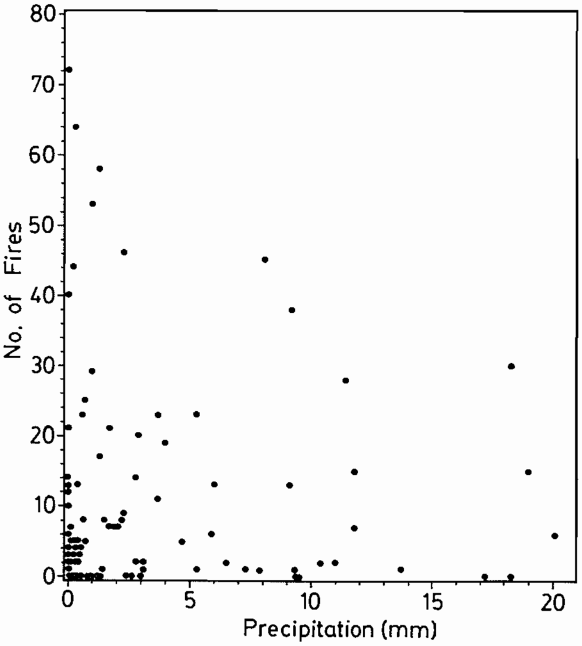

FIG. 8. Reported lightning fires versus precipitation.

and sometimes dry, organic material, an excellent medium for fire spread.

In the first regression model we used lightning discharge data as predictors for the number of lightning-ignited fires in UTM zone 15 for each day of the season. (In this paper the term predictor refers not to prediction but to terms that might make significant contributions to the explanation of variance in the data.) Predictors included the number of negative discharges, the number of positive discharges, the average (Daily average 00:00 to 24:00 eastern standard time) multiplicity of the negative discharges, the average multiplicity of the positive discharges, the average strength of the negative discharges, the average strength of the positive discharges, number of negative discharges times multiplicity of negative discharges, and number of positive discharges times multiplicity of positive discharges. Table 3 shows the results of running an SAS forward stepwise linear regression (SAS Institute Inc. 1985*a*). Terms were accepted only if they met the rather stringent 0.05 significance level, which corresponds to a minimum *F*-value for entrance of 4.0; terms were removed when they failed to meet a 0.06 significance level. The results show that 43% of the variance in lightning-ignited fire data was explained by the lightning data. The most important predictor was the average multiplicity of

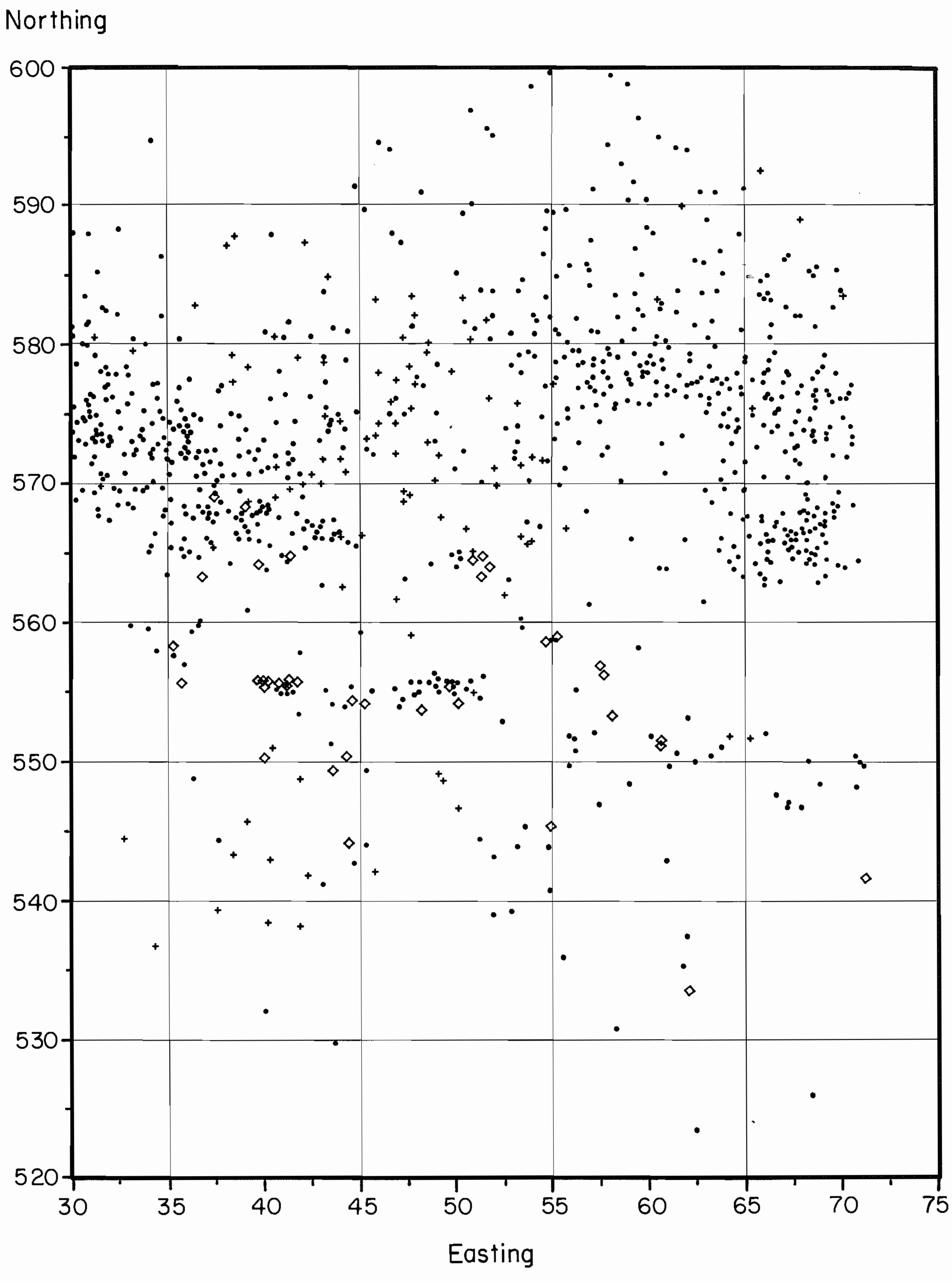

FIG. 9. Map showing locations of reported lightning fires (◇), negative lightning discharges (●), and positive lightning discharges (+) for May 25, 1988, over the Northwestern Region of Ontario.

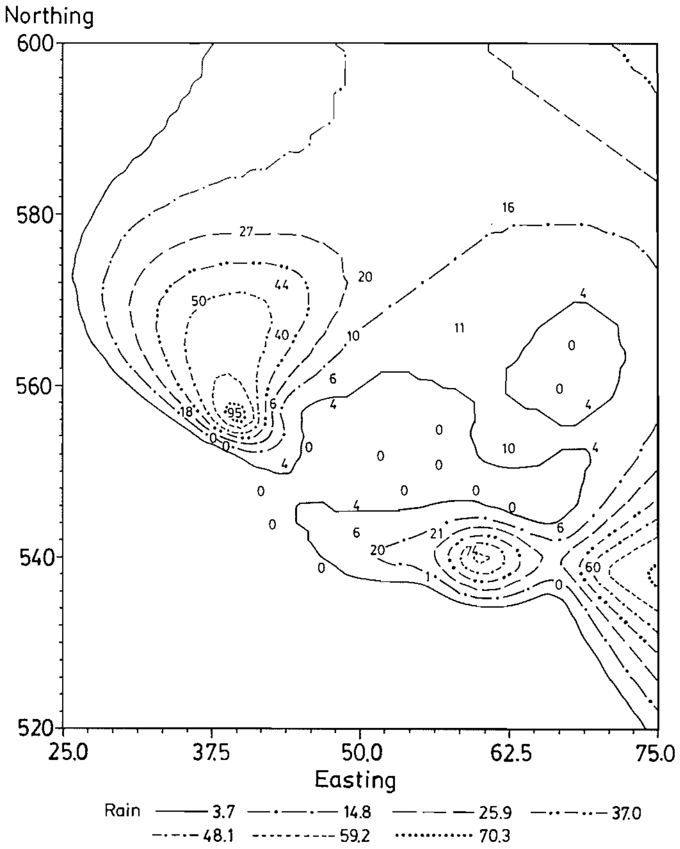

FIG. 10. Map showing weather station precipitation amounts (in tenths of a millimetre) for May 25, 1988, over the Northwestern Region of Ontario. Precipitation amounts have been placed where the weather stations are located (stations are at the bottom right of each precipitation amount).

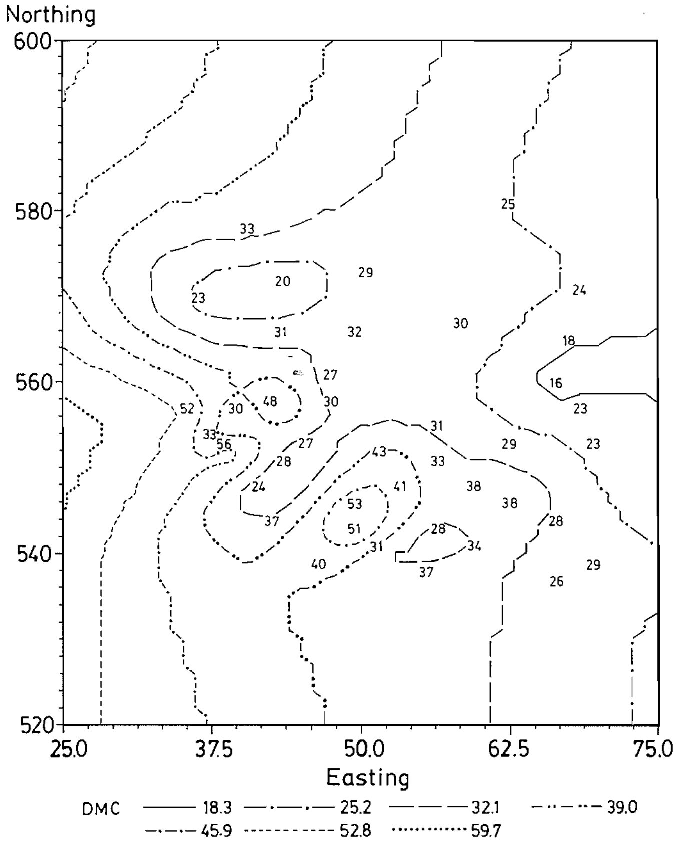

FIG. 11. Map showing weather station Duff Moisture Codes (DMC) for May 25, 1988, over the Northwestern Region of Ontario.

negative discharges, which explained about 24% of the variance. The strength of the negative discharge was selected second. Figures 2 and 3 show plots of the number of negative and positive discharges, respectively, versus the number of lightning fires ignited on a daily basis. Figure 4 shows the average multiplicity of negative strokes versus fire starts.

The second regression added weather variables and fire weather indexes to the predictors. The weather variables included temperature, relative humidity, wind speed and direction, and 24-h precipitation, all observed at 12:00 local standard time. The following fire weather indexes were used: Fine Fuel Moisture Code, Duff Moisture Code (DMC), Drought Code, Initial Spread Index, Build Up Index, and the Fire Weather Index. A forward stepwise linear regression was performed with the same conditions as outlined for the first regression. The results are shown in Table 4. The DMC was selected first, explaining 25% of the variance. Other variables selected include average multiplicity of negative discharges, number of negative discharges, and wind speed. All four variables explained 47% of the variance. Figures 5 to 8 show plots of the DMC, wind speed, temperature, and precipitation, respectively, versus the number of lightning-caused forest fires ignited on a daily basis.

A sample of the spatial relationship between lightning and fires for a single day can be seen in Fig. 9. Over this base map the predictors were plotted and an objective analysis was performed (using the procedure GCONTOUR from SAS/GRAPH version 5.0 (SAS Institute Inc. 1985*b*)). Figure 10 shows a sample of the overlaying procedure with precipitation for the same day (May 25) as that for Fig. 9. Figure 11 shows the DMC for the same day. This mapping procedure was carried out for a total of 19 days.

Despite the higher probability of a positive discharge having a LCC component, positive discharges do not appear to be the major factor in lightning-ignited forest fires because they contribute only a small proportion of the total discharges (~5%). The results of the regressions bear this out, with only predictors from negative discharges being selected. However, this does not imply that positive discharges should be ignored. As seen in Figs. 3 and 4, the number of discharges is not well correlated with the number of fires. The success of the multiplicity of the negative discharges in the regression is interesting. Shindo and Uman (1989) studied 90 negative cloud to ground discharges and found that only 1 of 19 single-stroke discharges was followed by a LCC, whereas 21 discharges of the remaining 71 multiple-stroke discharges contained a LCC (though some of these were after the first stroke). Thus their results support our finding that the frequency of LCCs is related directly to the multiplicity of the negative discharge. Increased probability of a LCC with multiple-stroke discharges leads to an increased probability of ignition.

The selection of the DMC as an important predictor is not surprising; the DMC represents the fuel moisture of loosely compacted decomposing organic matter (Van Wagner 1987). Many fires start at the base of a tree in the duff layer as the lightning discharges pass down the tree into the ground. From Fig. 5 it appears that there is a threshold

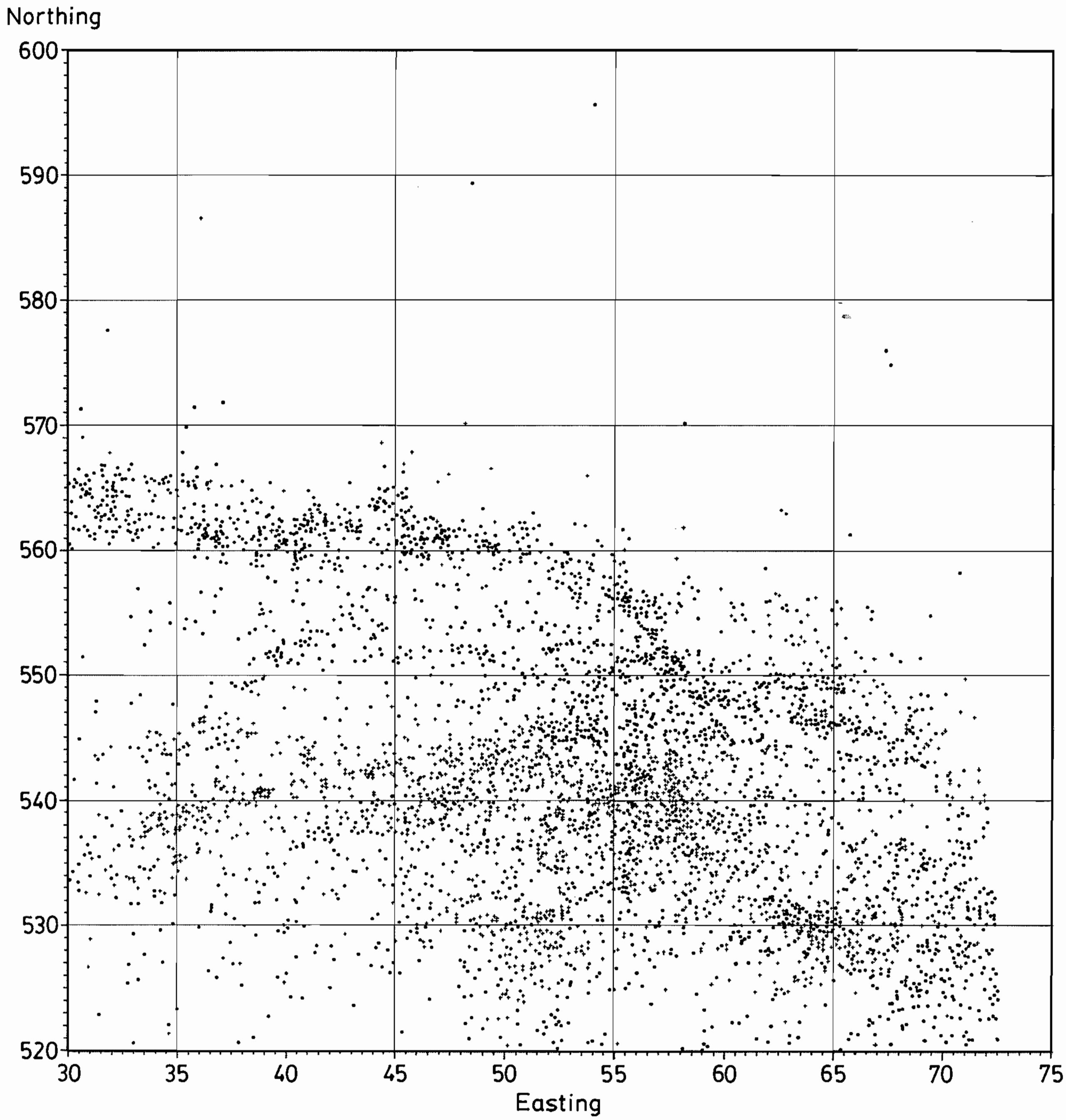

FIG. 12. Map showing locations of negative lightning discharges (●) and positive lightning discharges (+) for July 15, 1988. (There were no reported fires on July 15, 1988.)

value for the regional DMC of around 10 (a DMC value of 10 is equivalent to a moisture content of about 240%). Below this threshold the fuel is too moist for a fire to start. The actual moisture content for ignition may be locally different from the equivalent of a DMC value of 10 because this value was an area average. Conventional wisdom from the fire management agencies would suggest a DMC value of 20 as a threshold for fire occurrence. A threshold DMC value of 20 is also what Kourtz (1974) used in his fire prediction system. Although Latham and Schlieter (1989) studied the effect of fuel moisture as it affects the probability of ignition of wildland fuels, only moisture contents of 40% or less were tested. In his fire consumption experiments of duff from eastern Ontario pine forests, Van Wagner (1972) found no duff was consumed when the moisture content rose above 140%. In addition to fuel moisture, the inorganic content of the duff layer can also dramatically affect combustion (Frandsen 1987).

Precipitation that intuitively should have performed well was not selected and, in fact, had no correlation with forest fires. There are several reasons why precipitation was not selected in the regression analysis. First, the weather variables (temperature, relative humidity, wind speed and direction, and 24-h precipitation) had been averaged over a large area, so that even when there was widespread precipitation, there were some areas that received no precipitation. Second, some fuels were sheltered, for example, at the base of a tree, so that the fuels remained dry even with some precipitation. Radar precipitation data may provide some additional information on the spatial and temporal characteristics of the precipitation, but would not address the sheltered fuels problem. The mapping of precipitation (e.g., Fig. 10) provided many insights into the lack of correlation between precipitation and fire starts. Lightning and precipitation occur concurrently in this part of the world; therefore dry lightning storms are rare. Based on this sample, many fire starts were at the periphery of active lightning areas where precipitation is light or nonexistent. In some cases, small cells of lightning activity were responsible for starting a large number of fires. This indicates that the spatial distribution of lightning and precipitation was important. Extensive areas of lightning and precipitation were not conducive to outbreaks of fire. Figure 12 shows a very active lightning day with 4606 discharges and no fires. However, on days when lightning and precipitation were from a large number of small cells, such cells were associated with fire starts.

The lightning mapping procedure shows clearly that positive discharges did not play a major role in fire starts. Also clear from the mapping exercise is that the lightning and fire start data were at times inconsistent. One example would be the report of a fire start with no lightning reported nearby. Either the lightning data is incomplete (possible) or the estimated occurrence date of the fire is incorrect, which can also happen.

Another possible explanation is the holdover fire. It has not been dealt with in this study. A holdover fire occurs when a lightning discharge causes fuel to smoulder. Depending on weather conditions, fuel type, fuel bulk density, and fuel moisture, this smouldering could possibly last 7–10 days or more before becoming a forest fire or finally going out. The fire season for 1988 in the Northwestern Region of Ontario was dry, and most of the lightning-initiated fires became fires shortly after the lightning discharge, thereby reducing the number of holdovers. To better understand lightning-initiated forest fires, the holdover (smouldering) problem will have to be examined closely. When mapping the data in this study, many days were selected that had no lightning or fire starts for a number of days prior to the sample to reduce the effects of holdover fires. However, all the days were used for regressions, which included, on rare occasions, days with reported lightning-ignited forest fires with no lightning activity being observed.

Another problem related to lightning is the fact that lightning is random. The location of the lightning discharge depends on the electrical field at the time of breakdown of the electrical field. Even the composition of the forest may influence the probability of lightning starting a fire. The duff layer of needles sheltered under a conifer makes an excellent location for a fire to start in comparison to the duff layer in a hardwood stand. Thus certain geographical areas, because of their forest cover, may be predisposed to lightning fire starts.

Summary

Lightning-ignited forest fires have been an integral aspect of the forests in the Northwestern Region of Ontario. On a regional basis, nearly 50% of the variance in lightning-ignited forest fires can be explained by lightning and fire weather data. The DMC was the most important predictor in the regression, explaining 25% of the variance in lightning-ignited forest fires. Positive discharges have a poor relationship with fire starts despite a common belief to the contrary. The role of the multiplicity of negative-charged lightning discharges and its relationship with LCCs needs further study, as does the role of smouldering and holdover fires. Future work will consider holdover fires and will hopefully employ precipitation radar data. Finally, fire management agencies should obtain lightning detection equipment that will distinguish the LCC phase in lightning discharges to identify potential locations of fire starts.

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