The Distribution of Lightning-Caused Forest Fires in Québec, 1978-1992

by

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ABSTRACT

This study is more in the nature of "exploratory " than "confirmatory" in its exploration of the temporal and spatial patterns of lightning-caused forest fires in Québec, for the fifteen year period 1978 to 1992. Economic returns garnered from forest products, as well as species and habitat loss, make lightning-caused forest fires an important area for investigation.

Natural forest fires are affected by many factors. For the purposes of this study two classes of variables are used in the investigation of the location and timing of lightning forest fires; these are species and weather data. The species data is gathered at the zone forest level and forest age is used at a mature or young level. Weather variables are limited to temperature, precipitation and thunderstorms. These are selected as a result of agreement in related literature that they are valid variables to work with. Lightning-caused fires are mapped at various temporal scales and these are compared with the species and weather data.

The study reveals a dichotomous relationship, where fuel characteristics, or forest species, determine the location of fires (or spatial component), and weather dominates the temporal component.

Finally, an attempt was made to make generalisations based on the findings so as to identify issues for further research. Understanding the mechanisms which drive the occurrence and distribution of lightning-caused forest fires, is one of the first steps in creating lightning-caused forest fire models.

RÉSUMÉ

Cette étude est surtout orientée vers l'exploration plutôt que vers la confirmation. Elle explore les patrons temporels et spatiaux laissés par les incendies de forêt causés par la foudre. Elle s'oriente vers le Québec, pour la période s'étendant entre 1978 et 1992. Les enjeux économiques apportés par les produits forestiers, ainsi que la perte d'espèces et d'habitats, font de ce sujet une importante zone d'étude.

Les incendies de forêt naturels sont influencés par plusieurs facteurs. Pour le besoin de cette étude, deux classes de variables sont utilisées dans la recherche de l'emplacement et dans la période où le feu par la foudre a eu lieu; celles-ci sont les espèces et les données météorologiques. Les données sur les espèces sont rassemblées au niveau de la zone de la forêt. L'âge de la forêt est donnée selon qu'elle est mature ou jeune. Les données météorologiques se limitent à la température, aux précipitations, ainsi qu'aux orages. Ces variables ont été sélectionnées en accord avec la littérature sur le sujet, qui démontrent que celles-ci sont valables pour ce genre d'étude. Les incendies causés par la foudre sont cartographiées à des échelles temporelles variées, et sont comparés avec les espèces et les données météorologiques.

L'étude démontre une relation dichotomique, où les caractéristiques des espèces déterminent l'emplacement des incendies, tandis que la météorologie domine la composante temporelle.

Enfin, un essai a été fait afin de généraliser pour permettre l'identification de certains points pouvant être traités dans des études futures. La compréhension des mécanismes qui provoquent la présence et la distribution des incendies de forêts causés par la foudre est l'un des premiers pas dans la création de modèles. (Traduit par Patrice Munger)

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Chapter One

A Statement of Problem

1.1 Introduction

The study of forest fires is important at local, regional and global scales, from a physical and economic point of view.

Global processes are affected by biomass burning (Figure 1). Atmospheric chemistry is affected by the large amounts of trace gases released through combustion, mainly carbon dioxide (CO_2) and water vapour(H_2Ov).

The resulting loss of vegetative cover modifies the albedo and hence the radiation budget, influences the hydrological cycle and raises the likelihood of soil erosion (Chuvieco & Martin, 1994).

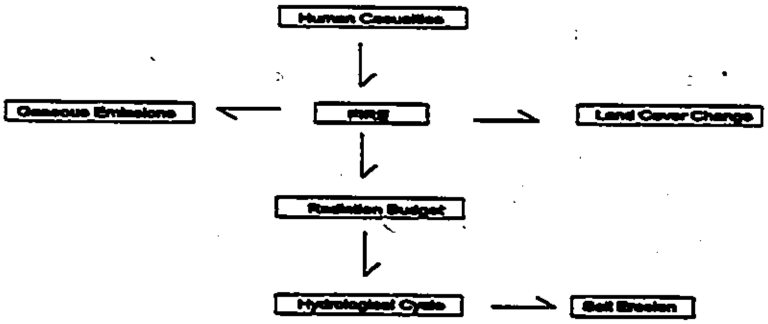


Figure 1. Global Implications of Biomass Burning (Chuvieco & Martin, 1994)

Carbon dioxide, methane, nitrous oxide and chloroflurocarbons are greenhouse gases implicated in global warming and climate change (Schlesinger & Mitchell, 1987). One of these gases, carbon dioxide, is stored in forests. Forests act as a carbon sink, removing carbon from the atmosphere and storing it until its release through fire, decay or forestry activities. Canadian forests are important as part of the global carbon balance, with the carbon store currently estimated at 224 million tonnes (Natural Resources Canada, 1994).

At regional and local scales, fires affect economies reliant on the forest industry (Standing Committee on Natural Resources, 1994; Gouvernement du Québec, ministère des Forêts, 1992) and also have strong effects on landscape and ecology (Chandler *et al*, 1983). The loss of forest cover bares soils to erosion and weathering processes. Forest burning also means the destruction of habitat for wildlife and can involve human casualties.

The necessity of preventing forest fires is incompatible with the knowledge that natural forest fires are, by their very definition, a natural phenomenon. They are part of forest ecosystem dynamics and as such play a valuable role (Chandler *et al.*,1983) in the propagation of some species, whose cones only open to release seeds at great temperatures. Fire also creates breaks in the forest necessary to the survival of many animals such as bear, deer, elk and owls. Forest creatures depend on the vegetation growing in these breaks as a source of food.

Apart from contributing to clean air and water, aiding as a protector against soil erosion and contributing to the regulation of local climates, forests also provide habitat for a wide range of plant and animal species. Canadian forests also generate $26 billion per year for the national economy through the tourism and recreation industries. Forests are also integral to hunting and trapping activities. Finally, forests are of spiritual value to most Canadians, as we identify with our national landscape and they are of particular importance to aboriginal peoples (Standing Committee on Natural Resources, 1994).

Fire can be a mixed blessing in northern climes where the breakdown of organic matter is slowed by cold. Partial burns can speed the recycling of organic matter and nitrogen; however, a severe burn can destroy all organic matter and all contained nitrogen is lost to the atmosphere (Chandler *et al*, 1983).

Forestry Canada reported in 1990 that Canada's forests accounted for 10% of the world's forested land; contained 16% of world softwood timber resources; and approximately 3% of global hardwood resources.

In 1993, Natural Resources Canada estimated that our $40-billion per year forestry industry generated employment for one in every 16 Canadians. Furthermore, they reported "the logging and forest services industries employed 61,000 people; the wood industries 132,000; and the pulp and allied industries 118,000; (....) accounting for 311,000 direct jobs". The forest sector's contribution to the GDP has increased every year since 1961, with a $19-billion net contribution to Canada's net balance of trade, by far the largest of any industry (Standing Committee on Natural Resources, 1994).

Québec's forest represents 2% of the world total. Québec contains some of Canada's richest stands of softwoods, and at 22%, Québec has the largest productive forest area in Canada. In 1976, the ministère des Terres et Forêts, divided the province's total land area, 1,647,640 km^2, into 3 zones: tundra, taiga and commercial forest. Two years prior to the study period, the commercial forest was estimated to cover 684,480 km^2, which represented 41.5% of Québec's territory. At this time, it was estimated that these lands were capable of producing 67,027,500 m^3 of wood annually (ministère des Terres et Forêts, 1976).

At the beginning of the study period, 1978, the commercial forest industry, in Québec, ranked first, in terms of the number of workers employed and wages paid, and second in terms of value added and value of shipments. The industry also ranked high in terms of principle manufacturing (ministère des Terres et Forêts, 1976). In 1976, it was estimated that 81,732 people were employed in the industry. In 1990, 190,000 Québec jobs were directly or indirectly linked to the forest industry (Gouvernement du Québec, ministère des Forêts, 1992).

1.2 Forest Loss to Fire

Québec possesses 1.1 million km^2 of forests, of which 490,000 km^2 are protected actively because of their economic importance (Gouvernement du Québec, ministère des Forêts, 1992). Human activity is considered to be responsible for an estimated 80% of all forest fires in the province, with lightning causing the remaining 20%. However, lightning causes the destruction of a greater area of forest than human activity. Since 1978, over 4.8 million hectares of forest have been destroyed by fire in the province of Québec. Acreage loss attributed to lightning is 4.2 million hectares. The combination of all other sources of ignition represent only 600,000 hectares. In 1992, the Government of Québec, Ministry of Forests reported that to meet economic threats, and "particularly the menace they represent" to ecological systems and human populations, the Québec government was attempting to create a unified fire-fighting system.

1.3 Objective

Forest fires do not occur in random locations at random times (Todd & Kourtz, 1990). Fires occur under specific fuel and weather conditions, creating distinct spatial and temporal distributions. It is critical to understand these two distributions in order to protect our economic and ecological interests.

Factors influencing fire hazard are usually studied independently of one another (Clark, 1989). This is due to the divergent nature of the variables. They are usually studied at different time scales, weather variables being monthly or daily values; fuel loading as a function of spatial pattern without dynamics; or climate scales which can range from decades to millennia (Clark, 1989). Each is a complete variable; any number of variables may be included in the analysis of natural fire occurrence and behaviour; weather variables may be smoothed over space and time; and fuels broken into many classes as having different flammabilities, moisture-holding characteristics and accumulation rates in forests (Clarke 1989; Chandler *et al.* 1983; Flannigan & Harrington 1988).

The objective of this research is to investigate selected distributional factors affecting the pattern of forest fires in the study area, and to determine which of these factors are important to the spatial and temporal instances of lightning-caused forest fires.

The research looks to the role of the selected variables as the basis of the pattern. The weather conditions linked to lightning-caused forest fire outbreaks are examined, as is, the role of species distribution and forest age, temporal and spatial variations and preferential geographic locations for fire outbreak.

Only ignition is studied in depth. Other variables, such as area burned, cost and economic loss may be referred to in general, but are not considered at length. The reason for this is the number of complicating factors influencing the excluded variables i.e. the area burned is tied to the distance of the fire from the fire-fighting station; and the costs related to a fire event are linked to the location of the fire fighters and their equipment and how efficiently they perform their task (Flannigan and Wotton, 1990; Stocks and Street, 1982). Area lost to fire is also linked to local environmental policy, as some fires are allowed to burn out naturally. This means that all other components, with the exception of lightning strikes, are influenced by other factors, although it could be argued that lightning-caused fires are influenced by human activity.

Chapter Two

Research Design

2.1 Study Area

The study area comprises the province of Québec to 54° north latitude and 61° west longitude. These boundaries are determined by the spatial extent of the forest fire data base used in the study.

The area is characterised by rugged shield topography, dotted with a multitude of lakes and waterways. In the north, the boreal forest landscape is marked by large tracts of even-aged pine and black spruce in a patchwork arrangement. To the south, the appearance of human activity increases in relation to the appearance of the leafy deciduous species. By the southern border there is little forest left and the landscape is completely dominated by urban or agricultural activity.

2.2 Forest Fire Components and Distribution

To investigate the distribution of naturally-caused forest fires, it is first necessary to understand the underlying dynamics of the processes and the contributing factors of forest fires in general, and lightning-caused fires in particular.

Forest fires are the result of the interaction of three variables:

Fuel + Oxygen + Ignition Source = Fire.

Forest fuel is usually composed of grass, leaves and wood. For naturally-caused forest fires, lightning strikes are usually the source of ignition (Chandler *et al.,*1983). For the purposes of this study, oxygen is considered to be homogeneous and is not discussed further.

Forest fires are intrinsically linked to weather and climate. Over a short period of time, weather influences the amount of moisture in the fuel and its ability to ignite and sustain combustion, whereas over a more prolonged period, climate influences the type and growth of the forests and therefore the amount and type of fuel available (Flannigan & Harrington 1991; Chandler *et al.*, 1983). Chandler *et al.*, 1983, summarize it as such:

> -climate directly influences the total amount of fuel; and the length and severity of the fire season; while
>
> -weather regulates the moisture/flammability of the dead forest fuels; and acts as an independent influence on the ignition and spread of forest fires.

2.3 Methodology

This research investigates the spatial and temporal pattern of lightning-caused forest fires in relation to selected weather, ignition and fuel variables to determine distributional factors affecting the spatial and temporal patterns.

The date, location and cause of all forest fires in the study area were obtained in order to determine the timing and geographic location of natural forest fires. The study variables (i.e. weather, species) are then reviewed in order to uncover how these variables contribute to the establishment of lightning-caused forest fire patterns, both spatial and temporal.

Sophisticated statistical tests are not employed in the interpretation of this data. Todd and Kourtz, 1990, in working on predictive models for forest fires noted that the use of these tests with historical fire data are precarious at best due to the inaccuracies in the fire information. Many other statistical maneuvers are also inappropriate because the data do not form a normal distribution.

Most literature concurs that the important research variables in forest fire investigation are:

fire data: the number of fires and their locations;
weather data: on temperature and precipitation patterns;
ignition variables: the number of recorded thunderstorms; and
fuel variables: the forest age and species distribution, and the percentage of forest cover (Harrington, 1982; Proulx 1989; Flannigan & Harrington, 1988; Flannigan & Van Wagner, 1991; Clark, 1989; Chandler *et al.*, 1983)

As with most research, the data review begins with an Initial Data Analysis (IDA), which is an informal exploratory look at the data (Chatfield, 1993). The IDA is used to clarify the general structure and quality of the data, process the data and apply the appropriate checks, describe the data, create summary statistics, graphs and tables.

An investigation of possible data sources found weather, fuel and forest fire information readily available. The data were obtained from the various sources. The IDA is completed, including a review of the various causes, a calculation of the area burned and the creation of numerous graphs, tables and maps displaying the data in many different ways.

2.4 Definition of the Data Base

The empirical component of the study required varied types of data, including historical forest fire information, species information, and weather data, from several sources. Data scrutiny, part of the IDA, assessed the structure and quality of the data and included all data transfers to appropriate formats.

2.4.1 Fire Data

Fifteen years (1978 to 1992) of historical lightning forest fire data were collected from the Société de Conservation de l'Outaouais. In 1972, Québec opted for a regional fire protection organisation. Under this system, the forest territory requiring intensive protection is covered by one of the seven "Sociétés de Conservation" which make up the provincial forest fire protection system. These non-profit organisations comprise forest licensees, owners of large private lands and the Department of Energy and Resources as the representative of the Government of Québec for public forested land (Gouvernement de Québec, ministère des Forêts, 1992). The government also represents the owners of private forests smaller than 811 hectares. All activities regarding the prevention, detection and suppression of forest fires are coordinated through the Société.

An extensive data base was created in 1972 to aid in the fight to control forest fires, and to function as a research base to increase understanding of the forest fire process in Québec. This data base can be used to create a historical profile of forest fire patterns. It should be noted, however, that the quality of all historical fire records is questionable and that, in some cases, the only certain fact is that a fire probably occurred (also see Todd and Kourtz, 1990).

Structurally, the data base contains seventeen fields (see Appendix I, for complete record layout). The data base originally carried information for only two small regions of the province. In 1978, most of the remaining areas of the province were added to the data base.

Data were collected for the following fields:

- fire number;
- year;
- month;
- day;
- status;
- grid location;
- region;
- cause;
- area burned; and
- cost.

In 1987, the data base was redesigned and fifteen new fields were added. These new fields are not used in this study, but are listed in Appendix I. A northern region was added to the data base, as late as 1991.

The data base contains records of 15,761 fires for the study years of which 3,507 are caused by lightning. The IDA revealed a small number of flawed records. An example of the type of data base errors found is the sixteen records which have a cause of less than 1, a value which is not an option in this data base. The flawed records remain in the study as information in other fields, such as month and year, are still useful to the study.

Certain alterations had to be made in order to create data acceptable to MapInfo, the mapping software used in the thesis. The Société de Conservation de l'Outaouais created a unique geographic grid referencing system that was not interpretable by MapInfo. The Société provided a software programme written in BASIC which, when translated into MAPBASIC, provided more usable latitude and longitude coordinates for the forest fires.

2.5 Geographic Referencing

First an overview, number of fires by cause and area consumed by fire, of all forest fires, is created from the data base. This provides insight into the role of lightning-caused fire in relation to other fire causes in the study area. A table links by cause, the number of fires with the hectares consumed, see page # 34. All of the fires that were lightning-caused are then extracted from the data base.

From the table of lightning-caused forest fires the number of fire for each degree of latitude and longitude for the study area were calculated. These were then recorded on a 1 x 1.5 metre sheet of mylar. This sheet of mylar was then used as an overlay for a series of base maps.

The natural forest fire data were then transformed into a series of maps created in MapInfo. This map series included:

- the relation of fire size to location;
- all lightning-caused fires occurring over the study period;
- a time series of maps was then created to show annual and monthly patterns of the total distribution;

- years with a large number of fires are mapped to compare with a similar number of low-fire years to determine if a geographic preference exists in times of intense burning.

2.6 Species Data

Forest composition information for the province was derived from the species distribution map, "Massifs boisés" which was created by the ministère des Terres et Forêts, direction générale des Forêts, service de l'Inventaire forestier in 1973, and provides a reliable depiction of the forest situation at the beginning of the study period. The mylar gid of latitude and longitude was overlaid on the map and the percentage of species per grid square calculated. A map of forest age was also created from this base map and all lightning-caused forest fires were overlain to determine the coincidence of fire and general forest age.

The more general forest zone information, is obtained from the "service de la Photogrammétrie et de la Cartographie, direction générale du Domaine territorial, ministère des Terres et Forêts du Québec".

2.7 Weather Data

All weather data were collected from Environment Canada. Information pertaining to mean monthly temperatures, mean monthly precipitation and the monthly sum of thunderstorms were gathered for the various stations (see Appendix II).

Temperature and precipitation data were more widely available than thunderstorm data, for the province of Québec. In order to maintain comparability between the weather variables, only stations collecting all of the study weather variables were used (see Appendix II).

The weather data were entered in tabular form by month and year, with totals and means calculated, and then isolines were created and mapped for the study area. The series of iso-maps are then compared to the total distribution of lightning-caused forest fires to determine if a visual coincidence exists.

A representative sample of five weather stations was selected to investigate further the link between weather and fire. Here a series of graphs are created showing the weather patterns in greater temporal detail for specific high and low fire periods. The five stations were selected for their location, as representatives of both frequent and infrequent fire sites. Further to this, Flannigan and Harrington (1988) in a study of wildfire and meteorological variables found only three reliable weather stations (Bagotville, Val d'Or, Maniwaki) in Québec, all of which are used in the sample.

Chapter Three

Fire Component Review

3.1 The Physics of Fire

3.1.1 Fire Profile

A forest fire does a number of specific things, the first of which is consume woody material. Second, it creates heat that may kill. In most fires, much more is killed, injured or changed due to heat than is consumed by flame (Chandler *et al.*, 1983). Lastly, it produces residual mineral products that may cause chemical effects, mostly in relation to the soil.

Forest fires consist of three varieties: surface fires, which burn litter and small vegetation; crown fires which advance through tree tops (the fastest spreading of all fires); and ground fires, which consume the surface material below the forest litter. Fire spreads most quickly when air and fuel are dry, and the fuel forms an open-matrix through which air, smoke, and the gases produced by combustion, can quickly pass (Chandler *et al.* 1983).

Ground fires are the least spectacular, and the slowest moving, but are often the most destructive and the most tenacious. In finely divided ground fuels such as peat or duff, the availability of oxygen is a limiting factor in the intensity of the fire (Young and Geise, 1990). The absence of oxygen results in a glowing combustion.

These fires are of very low intensity and spread slowly, yet persistently, across the forest floor.

The spread of crown fires varies according to species. This is especially true of conifer and broad-leafed trees (Young and Geise, 1990). These fires are common in conifer forests but are less usual in deciduous, hardwood forests. This is due to the chemical make-up and the moisture content of the fuels. In conifer forests, the probability of a crown fire is reduced if the forest is mature and there is little understorey (Young and Geise, 1990). Most crown fires start as surface fires that have reached the necessary intensity to consume live vegetation, especially where the lowest limbs are high above the ground.

3.1.2 Ignition

Flannigan and Wotton, 1990, note that lightning ignition of forest fires is dependent on several factors such as:

- type, density, and depth of fuel;
- fuel moisture;
- ventilation; and
- nature of the lightning discharge.

Surface-to-volume ratio and thermal absorbency of a fuel determine the manner and speed at which forest fuel will begin to burn. Surface-to-volume ratio provides a reliable indicator of both flammability and combustion due to the variation of heat transfer by surface area, and fluctuates greatly among different forest fuel types. Thermal absorbency relates to heat reflection and inward conductivity. Thermal conductivity is controlled by two variables: fuel density and moisture content. MacLean (1941), (Byram *et al.* 1952) showed that

$$K = ((4.78 + 0.97M)S + 0.568) \times 10^{-4} \quad (0<M<40)$$

$$K = ((4.78 + 0.13M)S + 0.58) \times 10^{-4} \quad (M>40)$$

where K = thermal conductivity in cal/sec cm^2 (°C/cm)

M = moisture content in percentage of oven-dry weight

S = specific gravity based on oven-dry weight and wet volume at M

Here, the effect of moisture is dependent on fuel density. The denser the fuel, the greater the effect of the moisture. The temperature will rise as a function of its density and specific heat. The specific heat depends on the temperature and moisture content, but is practically independent of specific gravity or chemical composition. The specific heat of dry wood is:

$H = 0.25 + .00013T$ (where T is in °C)

therefore:

for $t = 20°C$, $H = 0.63$

$t = 30°C$ $H = 0.644$

$t = 40°C$ $H = 0.657$

Moisture effects ignition by increasing the specific heat and thermal conductivity of the fuel, so that more heat must be absorbed in order for the surface to attain ignition temperature (Young and Geise, 1990).

Fuel will begin to outgas at a temperature of about 100°C (Young and Geise, 1990). Water is turned to steam in a process that requires high energy levels. Until the water has been evaporated there is little energy available to continue the process of distilling flammable gases and heating interior layers. Once it has been dispersed, the temperature at the fuel surface rises sharply and volatiles are produced.

Volatile mixtures surrounding igniting fuels are vulnerable to fire. If the volatiles are within their flammable range and exposed to heat, they will burn. If the mixture is too rich and there is not enough oxygen present, the mixture will not flame until more oxygen has been introduced. Excessive water vapour, or CO_2, reduces the relative amount of oxygen in the mixture and also prevents flaming. Similar problems arise if the mixtures are too lean. This can occur when the level of volatiles drops below a threshold limit, or when air movement causes too rapid a dilution of the mixture. Young and Geise, 1990, state that the flammability limits of forest fuels are directly related to their heat of combustion; therefore, the flammability limits depend on the kind and amount of volatiles and extractives. These are species and season related.

Reactions taking place under 200°C are endothermic. Once temperatures exceed 280°C, exothermic reactions predominate and the fuel has reached ignition if it is insulated from external cooling since the reaction will continue even if the external heat source has been removed.

3.1.3 Combustion

Once a forest fuel has ignited, the rate and intensity at which it will burn are affected by many different factors. Combustion in any but the thinnest fuels can be considered to be a series of ignitions as energy reaches progressively deeper layers (Young and Geise, 1990). All of the variables that come into play in ignition also effect combustion, with the addition of several others that have a marked effect on combustion.

Fuel size and arrangement play a significant role (Byram, 1958, Van Wagner, 1983). The rate of burning increases with increased fuel surface area, provided there is an adequate oxygen supply. Byram suggests as a point-in-case, that a pile of kindling will burn much faster than a pile of logs. Radiation and convection heat the surface of the logs but only conduction can carry the heat within the individual logs. This is a slower mechanism than the first two. The pile of kindling is much less dependent on conduction and therefore burns faster.

3.1.4 Fuel Loading

Total fuel loading (also known as fuel weight and/or fuel volume or phytomass), is the amount of plant material, both living and dead, found above the mineral soil (Chandler *et al.*, 1983). This definition excludes roots and animal life, but includes dead plant material and large pieces of woody material that have been killed, but not entirely consumed, in one fire, and left to completely burn in the next. Chandler *et al.*, 1983, cite the total physiological upper limit of phytomass for any site as:

$$W = 26\ A$$

where W = total phytomass in tonnes per hectare

A = stand age in years.

A given stand will reach this value based on site quality, independently of vegetation type. The future phytomass value can therefore be predicted for any time in the future by substituting *c* for the constant 26 in the equation, solving for *c* and computing *W* for the desired future stand age (Chandler *et al.* 1983). Note, no upper limit for this process is provided. The rate of phytomass accumulation varies throughout the forest-aging process and would not accumulate in a linear manner.

Van Wagner, 1977, in a study of age-class distribution and the forest fire cycle also looked at this assumption of uniform flammability with age and found little objective evidence to back-up the proposal. He did concede that older stands of conifers could be prone to lightning strikes due to the presence of scattered tall trees.

The advent of organized forest fire fighting and the managed forest, in the early 1900's, had an impact on the extent of fires, leading to an accumulation of forest fuels (Clark, 1989). These managed forests also bring an increased density to the forest. In a study at the Boise National Forest, it was found that a century ago a mature forest averaged one hundred trees per acre; in the modern, managed forest, densities can now reach 500 trees to the acre (Globe and Mail, October 10, 1994). This creates an overabundance of fuel, increasing not only the likelihood of fire, but also affecting the potential size of a fire.

3.1.5 Fuel Moisture

In living fuels, the moisture content of foliage and small twigs, the only living plant matter to play an important role in forest fire behaviour, is governed by physiological processes. Internal H_2O deficits are controlled by the rate of H_2O uptake through the roots and H_2O loss through transpiration. Transpiration is controlled by the environment, leaf structure, and the degree of stomal opening. Absorption is controlled by soil factors.

Within a given fuel type, fire behaviour is regulated by weather conditions, particularly atmospheric moisture (Byram 1959, Chandler *et al.* 1983, Young and Geise 1990). Fuel moisture is determined not only by the amount and the duration of rainfall, but also by relative humidity during periods of drought. Fuel absorbs moisture from the air and this moisture affects the amount of energy a fire must use to evaporate H_2O prior to combustion. This evaporation has a further damping effect as it reduces the amount of oxygen available for combustion. As humidity in the atmosphere drops in dry times, H_2O is evaporated into the air. The rapidity of the response of the fuel to relative humidity is dependent on the size of the fuel reservoir, fines responding quickly while larger fuels respond more slowly. Diurnal variations in the intensity of fires is evidence of the speed at which fines can give up their moisture to the ambient air.

Fire is also affected by atmospheric stability. In a stable atmosphere, winds are steady and horizontal; in an unstable atmosphere, however, gusty turbulent winds and vertical air motion prevail. Crown fires are more likely in these unstable conditions as the vertical air currents pull smoke and burning debris toward tree tops.

Dead forest fuels are hygroscopic, taking on or giving off moisture until the fuel is in equilibrium with the ambient atmosphere. Called the equilibrium moisture content, it is controlled by relative humidity and temperature and internal fuel properties. Chandler *et al.*, 1983, discuss the poorly understood forces that bind moisture to fuel and point out that they operate differently in absorption (rising humidity) and desorption (falling humidity).

Chandler *et al.*, 1983, discusses the equilibrium moisture content of wood as fuel moisture content does not, therefore, react immediately to changes in humidity. If pine needles reach a state of equilibrium at 20% relative humidity, the humidity would have to rise to 30% before a change in moisture content would take place. This is due to the variation between the desorption and absorption equilibrium moisture content values. The curves will vary according to species and are also weakly affected by temperature. The rate at which a fuel will reach equilibrium is dependent on wood thickness, since moisture can evaporate from the surface at a greater speed than it can diffuse to the surface.

3.2 Forest Zones and Types

The interaction of forest fires and the regeneration characteristics of the tree species is for the most part responsible for the kind of forest found in any given region. Areas prone to intense fires which kill all of the trees over a wide area and species type which are able to regenerate even though all of the individuals are killed over a wide area generally prevail throughout the study area (Van Wagner, 1983). These hardy species include black spruce (*Picea mariana*), jack and lodgepole pine (*Pinus banksiana and Pinus contorta*), trembling aspen (*Populus tremuloides*) and white birch (*Betula papyifera*) all of which are prevalent in the study area.

Heinselman (1981) found northern vegetation differentially adapted to gradients of fire frequency and fire severity. The northern biomes of the study area are predominantly the end product of the long-term influence of both human-caused and natural fire. This is in agreement with the popular literature.

Generally, Québec's forests include cool temperate and boreal species, and tundra, plus the transition zones of each: temperate/boreal and boreal/tundra. Three-quarters of Québec's forests consist of coniferous trees, mainly white and black spruce (*Picea glauca*) and fir (*Abies balsamea*), and one-quarter of deciduous trees such as white birch, yellow birch (*Betula alleghaniensis*) and red and sugar maple (*Acer rubrum*, *Acer saccharum*) (gouvernement de Québec, 1992).

Map 1., Québec's Forest Zones, was created and published by the service de la Photogrammétrie et de la Cartographie, direction générale du Domaine territorial, ministère des Terres et Forêts du Québec. From this map we can see the spruce zone, or pessière, of the study area as a fairly homogeneous block of conifers. 85 % of the region is dominated by two species: spruce and fir, while 10% is white birch.

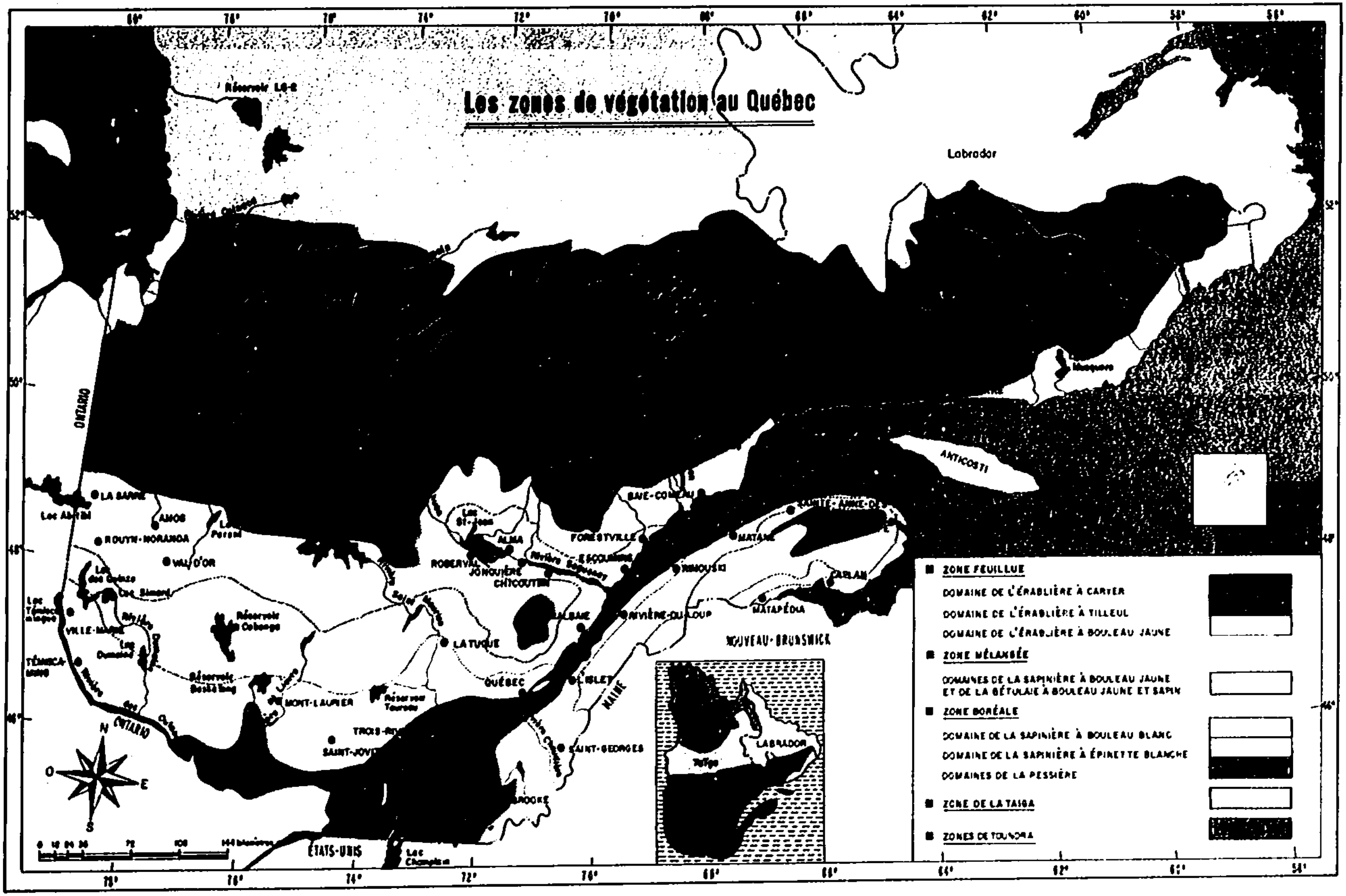
The fir zone, sapinère, represents a transition area between the conifers and deciduous forests. To the south, the area is composed of black spruce, fir, and yellow birch while to the north, white birch predominates.

Mixed forest would be the best description for the yellow birch-maple zone, érablière à bouleau jaune. It includes sugar maple, yellow birch, beech (*Fagus grandifolia*), fir, white birch and trembling aspen.

The laurentian maple zone, érablière laurentienne, is dominated by the sugar maple, although basswood (*Tilia americana*), American ash (*Fraxinus americana*), beech and butternut (*Julans cinerea*) are also frequently found.

The most southerly zone is the hickory-sugar maple zone, érablière à caryers. American ash, beech, basswood, white ash (*Fraxinus americana*), hickory (*Carya*), red and white oak (*Quercus rubra, Quercus alba*) and elm (*Ulmus americana*). This area contains species that are of great commercial value.

Les zones de végétation au Québec



Gouvernement du Québec
Ministère
des Forêts

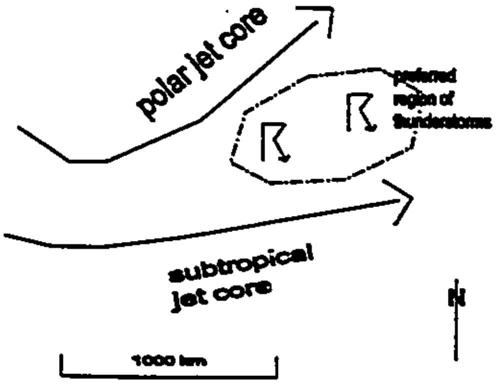
3.3 Québec Climate

3.3.1 Active Region

Climatic conditions in Québec are dominated by three major airstreams: cold, dry air from the Arctic; warm, moist air from the south seas; and mild, dry westerlies in between.

These air stream combinations, along with the height of the tropopause, 10 to 11 km, creates areas less thermally stable than other regions (Djuric, 1994). In the polar regions the tropopause is too low and the tropics have weaker storms because it is too high. Particularly favourable conditions are found in the mid-latitudes where polar and sub-tropical jet flow away from one another are seen, see Figure 2. This divergence leads to enhanced vorticity advection.

Figure 2. Divergent jet streams creating conditions for severe thunderstorms (Djuric, 1994).



Strong zonal patterns occurring throughout the year bring a mix of Pacific and Arctic airstreams. In winter, these systems involve moving highs associated with the southward push of Arctic air. This results in warm and cold conditions relatively speaking, with storms at the front.

When zonal flow is less vigourous and the trough over eastern Canada shifts west of the Mississippi Valley, cyclonic activity occurs in the Midwest United States. These southern anticyclonic airstreams move across Québec at intervals throughout the year and are the major source of precipitation and high winds. According to Hare (1974), in late autumn, winter and early spring their northeastward course typically takes the centres across southern Québec. These systems bring heavy snow and not uncommonly freezing rain at the fronts. Midwinter thaws in the southern part of the province are often due to this mechanism.

Long periods of warm and humid weather occur as the system centres move north. Heavy thunderstorms occur in the southern parts of the province, characteristic of the cold front belt. These belts are often preceded by a squall-line some 100 to 250 km ahead. Much of the summer precipitation occurring in the study area falls from the turbulent layer clouds containing local cumulonimbus cells. The precipitation pattern of intermittent rain, often heavy, with the occasional thunderstorm is typical.

Atlantic blocking can cause a major breakdown in weather patterns. Here the normal flow of the westerlies to the Atlantic is blocked by persistent ridges of high pressure in the central and western Atlantic. The resultant easterly airstreams from the Atlantic spread westward within the circulation of stationary cold lows (Hare &

Hay, 1974). In winter, this produces cloudy, mild weather and in summer it causes cool, showery weather. Once established, these patterns are very persistent. These stationary highs, resulting from the blocking patterns, are strongly associated with severe fire weather (Stock and Street, 1983).

Several studies of the weather/fire link have focused on the years 1970 to 1980, which had extreme variations in meteorological conditions, which in turn had a significant impact on many social and economic activities around the world. During this period, well-entrenched high pressure systems over central regions of North America effectively blocked spring precipitation from reaching northern areas in 1974, 1976, 1977 and 1980, creating prolonged warm, dry periods (Stocks & Street 1982; Harrington, 1982). These climatic anomalies produced a dramatic increase in forest fire activity and northwestern Ontario lost over two million hectares of forest in the ten year period (Stocks & Street, 1982).

Hare and Hay (1974) note another anomaly commonly appearing in spring, the presence of strong, stationary anti-cyclones over Hudson Bay. Once established, these high pressure systems maintain a flow of cold, clear and extremely dry Arctic air across the region.

The annual rainfall of the study area is greater than areas to the west. This is due to the flow of moisture from the Gulf of Mexico, the Caribbean and the subtropical Atlantic. Hare (1974) has commented that this rainfall may however be once removed, as it has been precipitated and re-evaporated over the United States before reaching Canada. Payette *et al.* (1989) note that Québec is influenced by a two-component transcontinental moisture gradient, with air humidity decreasing from south to north and increasing from west to east, (also see Barry and Hare, 1974).

3.3.2 Lightning

Before a fire can develop there must be a source of ignition. For natural fires, this source is lightning. This phenomenon usually occurs during a thunderstorm. Thunderstorms are local-scale phenomena that are possible virtually anywhere in the world. According to Henderson-Sellers & Robinson (1986), the basic prerequisite for a thunderstorm is an unstable, usually highly unstable, humid atmosphere, that easily triggers vertical motion.

Lightning is the result of charge separation within a thundercloud. The effect of the separation is a gradient of electrical potential both within the cloud and between the cloud and the ground. Once the gradient exceeds a threshold, a lightning bolt results. "This stepped ladder is met by a "travelling spark", with the "return stroke" flowing in the channel created by the two ... which may be followed by one or two "streamers" and by a second return stroke" (Henderson-Sellers & Robinson, 1986). In fact, most lightning flashes are made up of three or four strokes about 50ms apart.

Virtually all lightning-caused fires are the result of the long-continuing current (LCC) phase of the lightning strike (Flannigan and Wotton, 1990). However, not every LCC strike will start a fire and not every lightning bolt contains an LCC phase.

Chapter Four

Lightning-Caused Forest Fire in Québec

In this section, the lightning-caused forest fire record for the study period is analyzed and compared with the three weather variables, temperature, precipitation and thunderstorms, and forest species data. The record is subsequently broken down into annual and monthly distributions and again compared to the weather and species information.

4.1 Forest Fires

Over the study period, 1978-1992, there are 15,730 forest fires recorded in the data base, with a total area burned of 483,466.14 hectares. The study area experienced an annual average of 233 fires, consuming over 32,231.076 hectares of forest per year. There are substantial fluctuations from year to year for both the number of fires and the area destroyed, as seen in the following tables and graphs.

The data base recognises eight causes for forest fires in the province. These are: lightning, railway lines, forestry, industry, arson, residents, recreation or other. Table 1., Comparative land area destroyed by cause in Québec, from 1978-1992, lists the cause, area destroyed by forest fire and number of fires by cause.

Table 1. Comparative land area destroyed, by cause,

in Québec from 1978-1992

Cause	Area / hectares	Number of Records
Lightning	421,364.91	3,507
Railway	135.5	465
Forestry	21,017.43	995
Industry	3,147.13	1,730
Arson	505.07	766
Residents	982.04	3,182
Recreation	35,485.76	4,952
Other	828.30	133
Total	483,466.14	15,730

totals do not match due to errors in the data base

Recreation (4,952), lightning (3,507) and residents (3,182) are the three major causes of forest fires in the study area. It is apparent from the table that the greater number of fires is caused by recreation (4,952), with lightning (3,507) second; however, the greater loss of forested area is attributed to lightning. 385,879.15 hectares more are destroyed by lightning-caused fire rather than recreation caused fires. Residential fires, with the third greatest number of fires (3,182), result in a loss of only 982.04 hectares, which ranks fifth after lightning

(421,364.91 ha), recreation (35,485.76 ha), forestry (21,017.43 ha), and industry (3,147.13 ha).

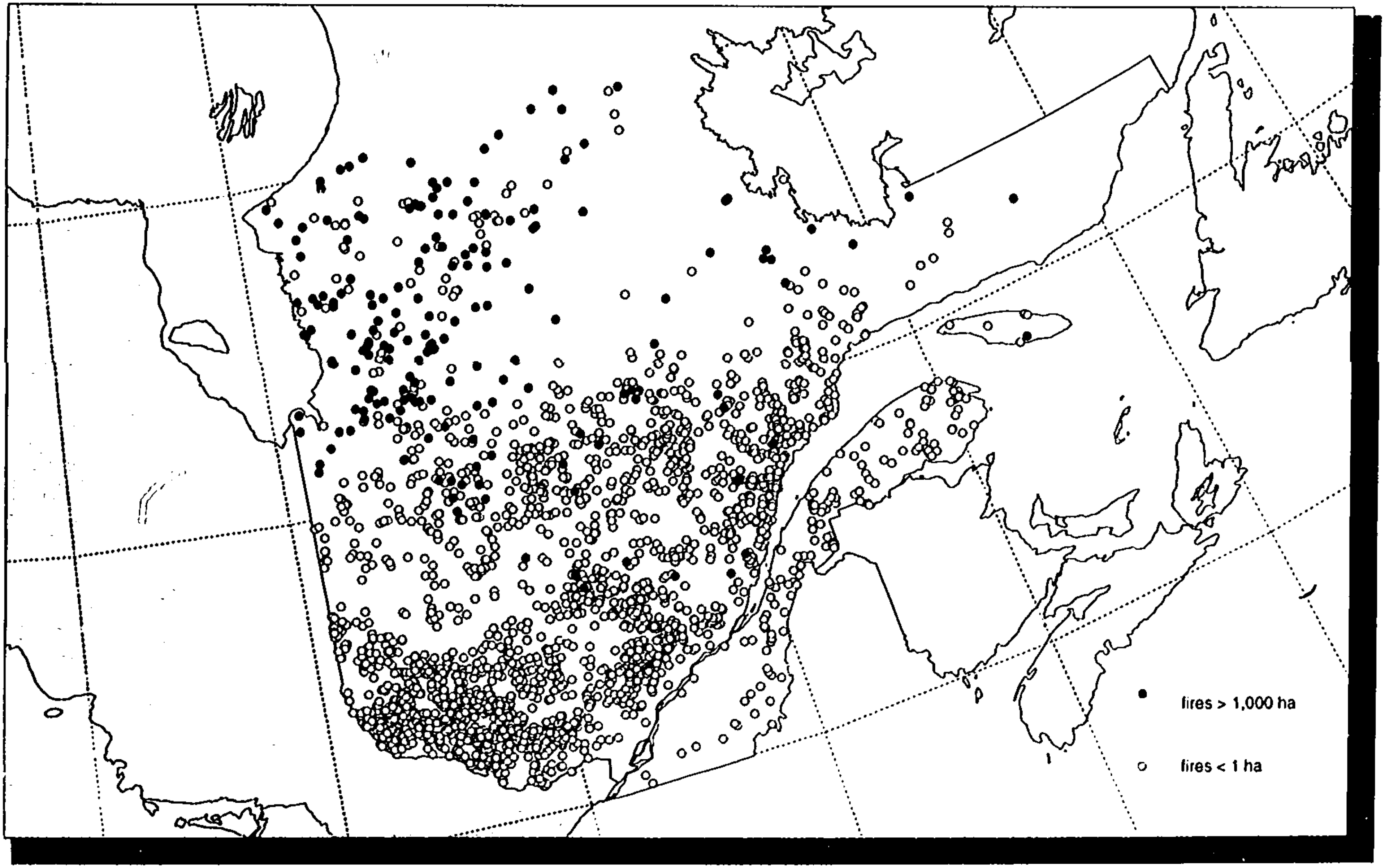
Lightning-caused fires destroy more forest than all other causes of fires combined. This great discrepancy in the area lost to forest fire may be due to the fact that, by definition for the Société du Conservation du l'Outaouais data base, a lightning-caused fire is one that must be reported by pilots, and therefore must burn until large enough to be noticed. The size of a fire also varies as a function of the distance from an organized fire-fighting station; by the perceived economic worth of the forest; the degree of difficulty in reaching the fires; the number of fires burning in other locations may dissuade fire fighters from going to a lightning-caused fire in a remote place; or oppositely, in a slow year fire-fighters may respond to areas where in normal years they would not; and finally lightning-ignited wildfires tend to occur as multiple occurrences, and severely strain fire-fighting capability (Stocks & Street, 1982; Flannigan and Wotton, 1990). As a result, lightning-caused fires can be quite large upon discovery.

Human caused fires are usually located where land is considered more valuable, therefore, detection is early and response swift.

Map 2., Lightning Fires, Size Comparison shows the plot of lightning-caused fires consuming in excess of 1,000 hectares verses fires with less than a one hectare loss. The map clearly shows all but fourteen large fires occur above 50° north latitude.

The map does show that the vast majority of fires are quite small. These are usually lightning ignitions that failed to spread, spot fires that are rapidly extinguished by accompanying precipitation and burns that begin on uplands and fail to move across adjacent wetlands or other physiographic features which serve as firebreaks (Foster, 1982).

Fire Size Comparison



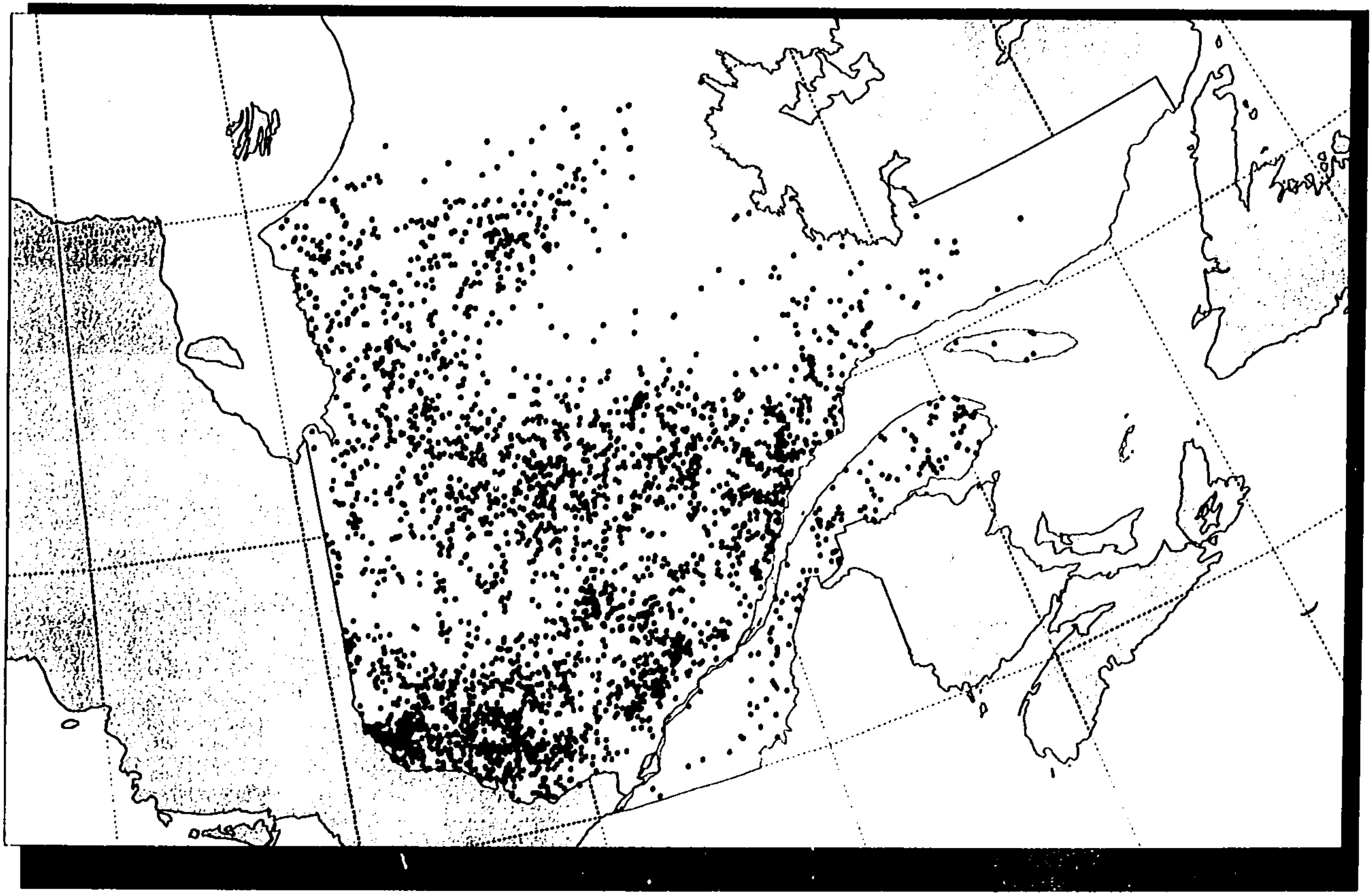
scale 5 cm = 448 km

4.2 Lightning-Caused Fires

Map 3., Lightning Fires, 1978-1992 portrays the total incidence of lightning-caused fires for the fifteen study years. A decrease is apparent in the frequency of forest fires, from south to north, and from east to west. The maximum number of fires, by square degree latitude and longitude, for the western boundary is 156, the southern boundary 32, eastern boundary 20, and the northern boundary 5. The forest fire maximum is found in the southwestern portion of the province where the forest fire total for the study period reaches 198 for the grid square 75° to 76° west longitude and 46° to 47° north latitude. The mainly deciduous and mixed forests of the southwest are dotted with several large reservoirs, the Cabonga, the Baskatong, and the Taureau, plus numerous lakes.

A secondary maximum occurs along the north shore of the St. Lawrence River. The secondary maximum, experiencing 84 lightning-caused fires, is located between 69° and 70° west longitude and 48° and 49° north latitude, an area bisected by the St. Lawrence. Vast areas are covered by water in this region; Lac Saint-Jean, Réservoir Gouin, Réservoir Pipmucan, Lac Mistassini, Lac Albanel and Réservoir Manicouagan all of which remove the possibility of fire. The forests are characterised by mature conifers, composed mainly of spruce and fir.

Map 3. Lightning-Caused Forest Fires, 1978 - 1992



scale 5 cm = 448 km

There is a comparative absence of fire in the eastern, north central and western regions of the province. No fires are recorded in the data base at a latitude greater than 55° north or east of 61° west longitude. These areas are mostly spruce in the east; spruce, taiga and tundra in the north; and fir in the west.

A zonal distribution is apparent (see Map 3. Lightning Fires, 1978-1992) in which three bands of fire traverse the province. The bands hover around 46° north latitude, 50° north latitude and 59° north latitude. Forest fires are less prevalent between the horizontal bands and in the western region south of James Bay.

4.3 Lightning-Caused Fire Distribution and Forest Types

In order to determine the spatial relationship between species type and fire, an overlay of all lightning-caused forest fires is created from the total forest fire coverage, and overlaid on both the species distribution map, ("Massifs boisés", created by the ministère des Terres et Forêts, direction générale des Forêts, service de l'Inventaire forestier in 1973) and the forest zone map (from the "service de la Photogrammétrie et de la Cartographie, direction générale du Domaine territorial, ministère des Terres et Forêts du Québec").

The maps reveal few fires in the hickory-maple zone. This may not be, however, a reflection on the woodland species, but rather the lack of forest cover in this area. Forest cover in the hickory-maple zone is limited by the concentration of urban and agricultural activities. This reduces fuel availability and consequently the number of lightning-caused forest fires.

The concentration of human activities also limits forest growth along the south shore. In fact, during the study period, only nine lightning-caused fires are recorded in the laurentian maple zone and hickory-maple zone. The frequency of fires increases in the conifer and yellow birch-maple forest of the south shore.

The greatest concentration of fire in the southwest involves mainly the mature forests of the yellow birch-maple zone and the laurentian maple zones.

There is a decrease in the number of natural forest fires at the transition zone of the boreal and temperate forests and again, approximately at the edge of the boreal forest and the taiga. The distribution of fires in the conifer forests of the study area is patchy, but fire frequency clearly increases in the mid-latitudes of the spruce zone.

In the mid-latitudes, the area south of James Bay, has few lightning-caused fires. This area is located in the fir and spruce zones.

Fires are also present in the northern spruce forests of the taiga. There are more fires to the west of this northern region. The forest distribution maps shows the eastern landscape was burned off to a great extent prior to the study years. Lightning-caused forest fires do not occur in the north as frequently as they do in the deciduous or fir forests of the south.

4.3.1 Forest Age

Forest cover is categorised as young or mature in terms of the general age of a stand. An age map, Map 4. Forest Age, based on four categories: young forest, mature forest, spruce or burned, is created from the base species map "Massifs boisés" prepared by ministére des Terres et Forêts, direction générale des Forêts, service de l'Inventaire forestier. This map does not differentiate the age of spruce forests. A map of lightning forest fires is overlaid on the forest age map in order to determine if a visual coincidence is evident.

The oldest stands of deciduous forests are located mostly in the south west corner of the province, excluding a narrow southerly margin. The oldest conifer stands are mainly north of 49° north latitude, west of 74° west longitude and south of 52° north latitude and continue to the Seaway. North of 51° north latitude, the land is mostly burned off with pockets of conifers and spruce.

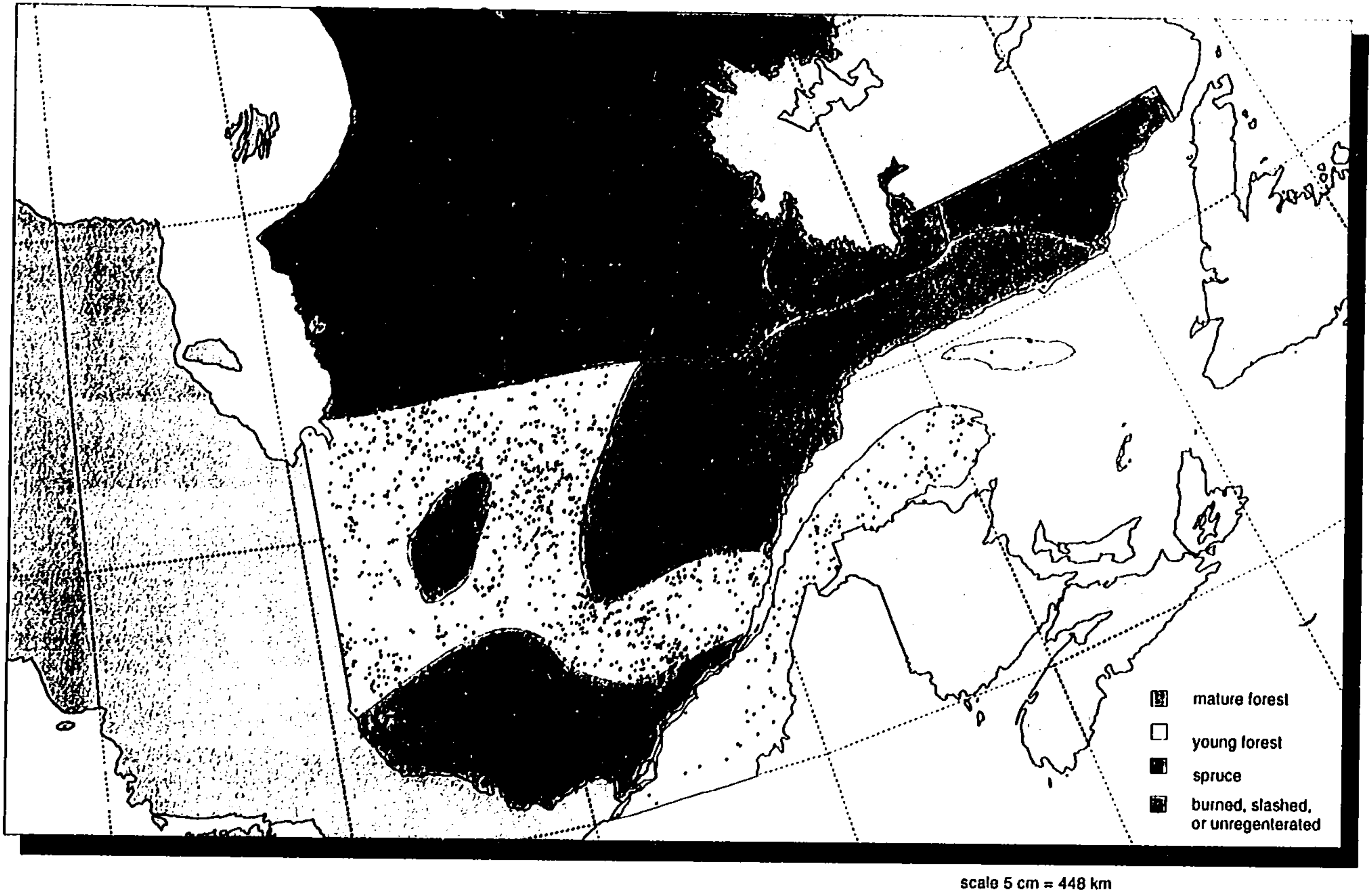
The process is then repeated for the monthly and annual lightning-caused fire distributions. The overlays show that regardless of temporal interval, fires occurred most frequently in mature forest. This applies to both the deciduous and coniferous forests.

Visual inspection of the location of the two variables, fire and forest age, revealed a connection between the generalized age of the stand and the number of lightning-ignited fires. Mature forests had a greater incidence of lightning-caused forest fire than young forests.

The base map "Massifs boisés" also displayed burned forest area. This is concentrated in the north-eastern section of the study area. These tracts of fire consumed landscape are more prevalent in the north than in the south yet this area experiences fewer fires. Given that the size of the fires is many times larger here than in the south then fewer ignitions could create a greater loss of northern landscape.

Payette and Gagnon (1985) hypothesized that a general decrease in regional spruce and increase in Forest-Tundra may be caused by long-term deforestation of the northern Boreal Forest induced by wildfires. The resulting expansion of treeless environments could have dramatic effects on fire regimes.

Map 2. Forest Age, 1973



4.4 Annual and Monthly Lightning Forest Fire Patterns

In this section of the paper temporal and locational aspects of the data are inspected by year and month, and each sub-set mapped and compared with species and weather maps.

The yearly data are culled to produce eight extreme years which are examined in depth to ascertain if a relationship exists between weather variables and the distribution of lightning-caused fires.

4.4.1 Temporal Variation

Table 2. Annual and monthly distribution of lightning-caused forest fires, 1978-1992, records the temporal variation of the lightning-caused fire record showing the monthly and annual totals and means. The annual fire totals range from a high of 485 in 1983 to a low of 60 in 1984. The annual means, calculated on fires occurring from April to September, fluctuate from an average of 10 fires/month in 1984, to 81 fires/month in 1983.

The monthly totals peak at 1,402 for the month of July, with the minimum number in April (11), the first month in the fire season. The last month of the fire season, September, has by contrast, a total of 119 fires with an average of eight per year. The highest monthly mean number of fires occurs in July (93), with June second (68) and August, third (46).

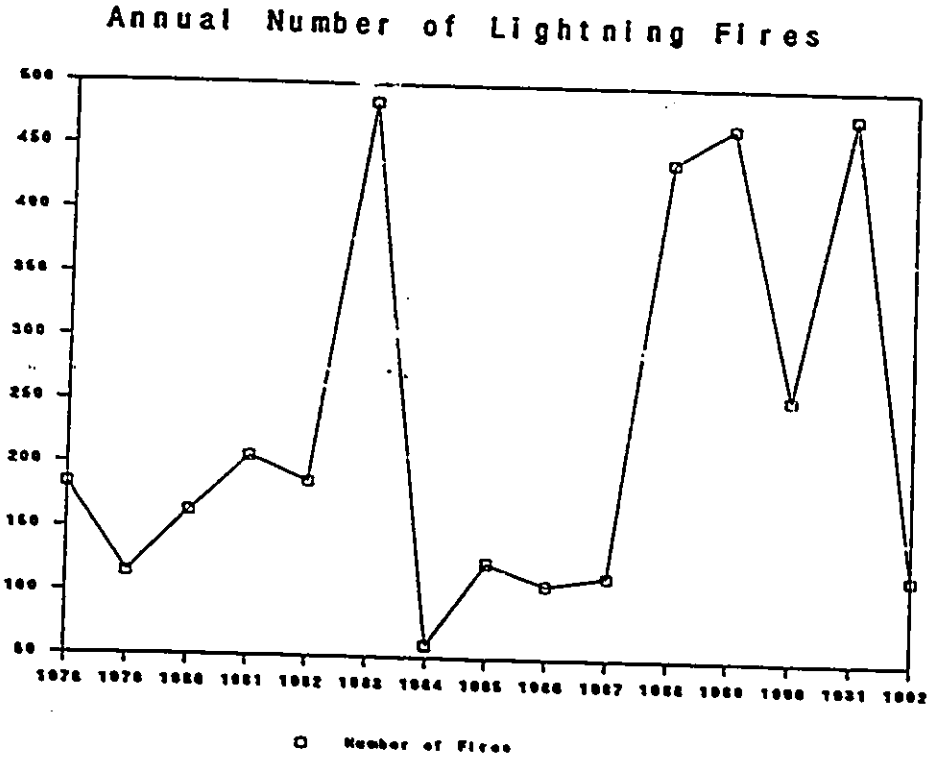
Table 2. Annual and Monthly Distribution of Lightning-Caused Forest Fires, 1978-1992

	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	Total	Mean
Apr	0	0	0	0	0	0	10	0	0	0	0	0	1	0	0	11	.7
May	15	5	21	5	43	0	1	8	74	12	27	1	19	7	24	262	17
Jun	22	22	34	11	64	239	6	24	4	28	126	134	19	225	61	1019	68
Jul	92	75	46	99	45	71	24	48	19	66	250	263	111	157	16	1402	93
Aug	54	11	62	89	34	144	17	23	11	8	36	66	34	89	16	694	46
Sept	1	2	0	2	1	31	2	2	0	1	1	4	72	0	0	119	8
Total	184	115	163	206	187	485	60	105	108	115	440	468	257	478	117	3507	234

4.5 Annual Patterns

Lighting-caused fires for individual years are mapped and compared to species and weather variables.

Figure 3. Annual Number of Lightning-Caused Forest Fires



There is considerable difference in the total number of fires occurring from one year to the next. The distribution maximum is 485 fires and minimum 60 fires, occurring in juxtaposition, in 1983 and 1984 respectively.

During the first ten years of the study period there are only two years which number more than 200 fires. In the last five years, four of the records are over 200, three of these are greater than 400. This creates a bimodal distribution, with the yearly fire totals either over 400, or under 200, with one exception occurring in 1990 (257).

Compared to the first ten years of the study period, 1983 and 1984 are quite anomalous. However, 1983 would not be out of place in the company of the years 1988 to 1991. 1984 had very few fires and there is no other section of the record that is similar in fire-number.

In summary, not including 1990, there are four years with a high rate of lightning-caused forest fires (1983, 485; 1991, 478; 1989, 468; 1988, 440) and one year with a low rate (1984, 60). All other records are unremarkable; their numbers of lightning-caused fires falling between 108 and 206 per year.

All of the fire locations are mapped by year, see Appendix IV, Maps 16 to 30.

4.5.1 Fire Present Areas

Three concentrations of lightning-caused forest fires appear repeatedly in the annual Lightning Fire Maps. These fire clusters are located in the southwest corner, the mid-latitudes of the study area, and in the north to the east of James Bay.

The fires of the south-west are typically located west of 75° west longitude, east of the Québec/Ontario provincial border and south of 48° north latitude. This area experienced 934 fires over the study period. Fires occur in this region in every year of the study. In many years, the fire pattern continues to the east, up the St. Lawrence River, merging with the eastern most secondary maximum.

The southwest area coincides with the forests of the laurentian maple zone and the yellow birch-maple zone. The laurentian-maple forests dominate the southwest region of the province and continue along the north shore of the St. Lawrence River to just north of Québec City.

The secondary maximum of the mid-latitudes is generally located between 45° north latitude and 50° north latitude. In some years, fires are strewn across a mid-province fire belt, and in others they are concentrated in the east, west or mid-section of this fire belt. In years with over 400 fires, the fires of the southwest and southeast merge. In 1980 (163), 1981 (206) and 1986 (108) fires tend to occur more in the west of the province, while in 1979 (115), 1987 (115), 1988 (440) and 1992 (117), the fires are located more to the east, near the Seaway. Fires across the fire belt occur in 1978 (184), 1980 (163), 1982 (187), 1983 (485), 1985 (125), 1988 (440), 1989 (468), 1990 (257), and 1991 (478). This zonal distribution can be clearly seen on the annual fire distribution maps in Appendix IV. For five of the fifteen years the zonal pattern is poorly defined, 1981, 1983, 1985, 1987, and 1991. Three of these five years have over two hundred fires, 1991 (478), 1983 (485), and 1981 (206); while 1985 had 125 fires and 1987 had 115 fires.

The lightning-caused fires of the north occur south of 55° north latitude, north of 51° north latitude, west of James Bay and east of 69° west longitude. They are present in every fire year, including 1983, when only 60 fires occurred, 13 of these are in the northern sector.

Fire pattern in this region is usually concentrated near James Bay, decreasing at the southern margin toward the east. The forest zone maps reveal an area comprised mainly of taiga with some spruce along James Bay. The more detailed forest species map reveals vast areas of burned and treeless landscapes.

4.5.2 Fire Absent Areas

Equally as important as where the fires are, is where they are not. Fires do not occur in areas of high population density or intense agricultural use. This is apparent on the south shore of the St. Lawrence and on the north shore line to Québec City.

In the study area, the largest area without fire is in the aforementioned northeast region of the province. This landscape is scarred by extensive fires, here great expanses forest have been slashed or disease-destroyed and are now only dotted with patches of spruce forest.

The western provincial boundary (above 52° north latitude to the southern tip of James Bay and west of 75° west longitude) also has relatively few fires. The forest zone map shows this area to be fir, spruce and taiga. The forest distribution map shows the area as dominated by young conifers.

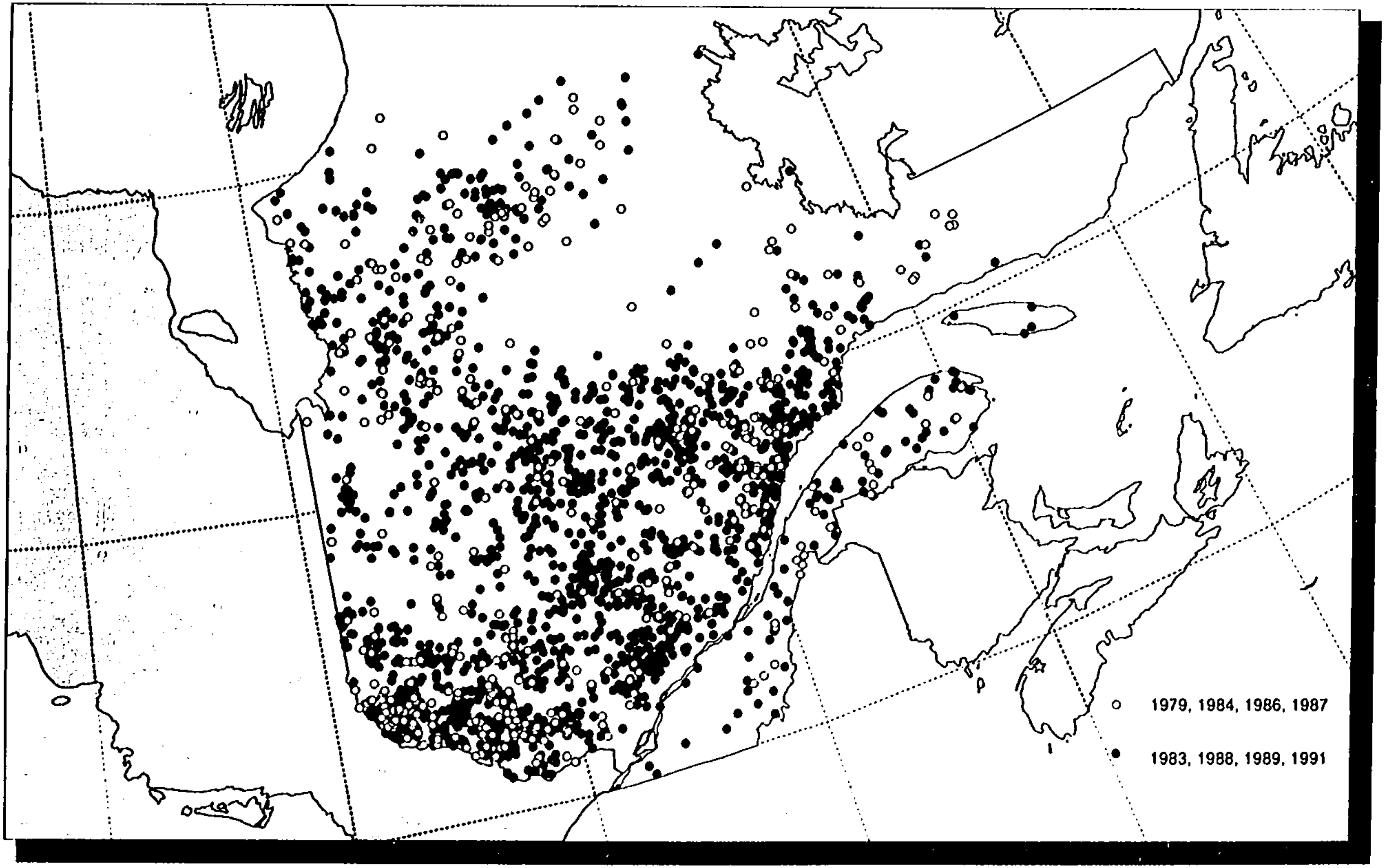
4.6 Comparison of High and Low Number Fire Years

To determine if there is a difference in the spatial patterns for years with a large number of fires and those years experiencing a small number of fires, two categories, high number of lightning-caused fires and low number of lightning-caused fires, are extracted from the database and then mapped, see Map 5. Comparison of High and Low Fire Years.

The high fire-number sample contains the years, 1983 (485), 1991 (478), 1989 (468) and 1988 (440). The low fire-number years are composed of 1984 (60), 1979 (115), 1986 (108) and 1987 (115).

The cartographic comparison reveals no spatial preference for forest fires in years of high fire-number prevalence or low fire-number prevalence. Both of the distributions are present in the south, at the mid-latitudes and in the north.

Comparison of High and Low Fire Years



scale 5 cm = 448 km

4.7 Monthly Patterns

4.7.1 Lightning-Caused Fires by Month 1978-1992

The number of fires occurring is much more consistent when examined at the monthly, rather than the annual interval.

Figure 4. Total Number of Lightning-Caused Forest Fires per Month

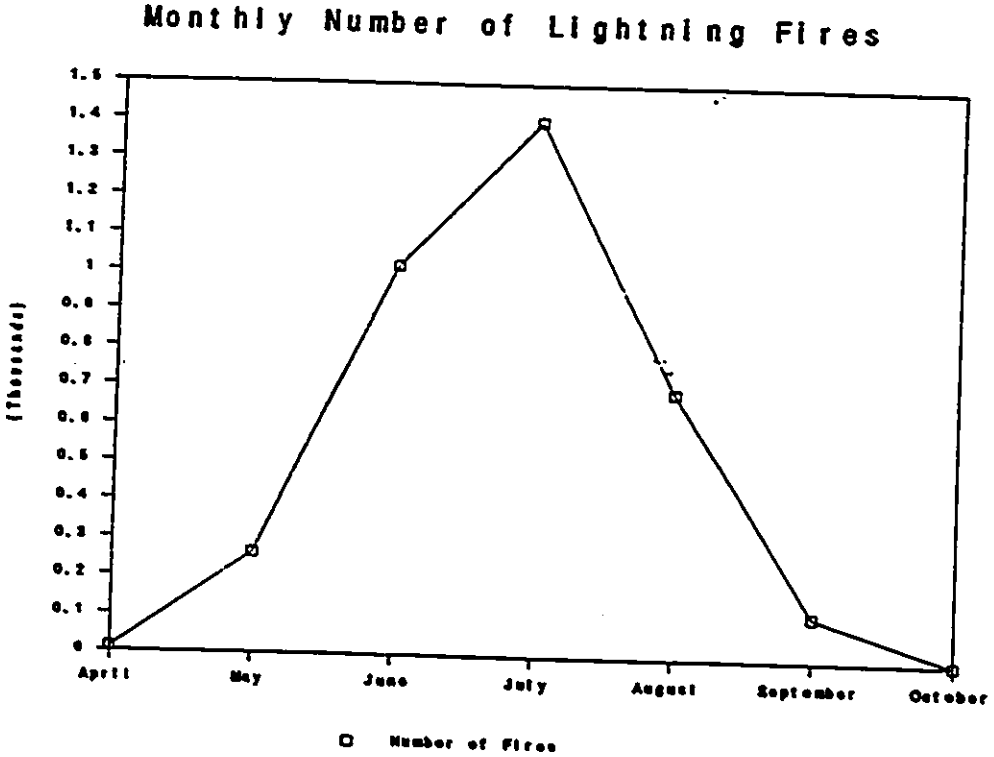
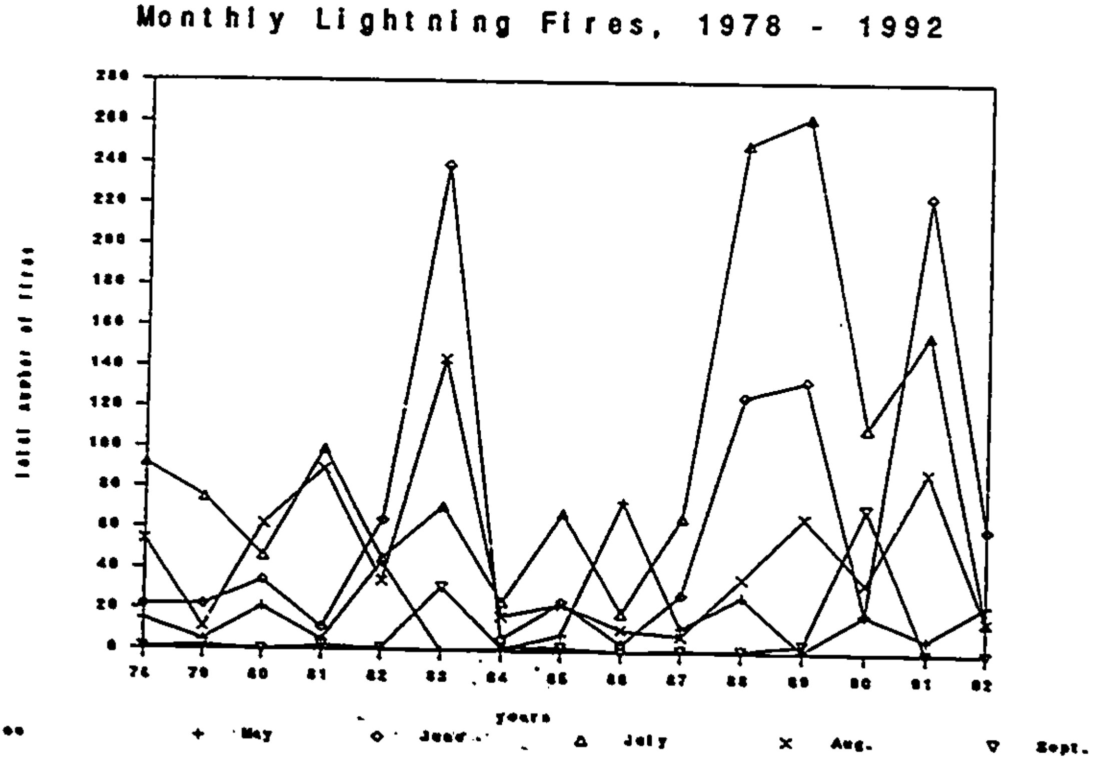


Figure 4. Monthly Number of Lightning Forest Fires, 1978-1992, shows the total number of fires occurring, by month, over the fifteen-year study period.

The maximum monthly total number of fires occurs in July, although the greatest loss of forest acreage occurs in June. More fires occur in the first two months of the fire season than in the last two. The total for May and June is 1,281 while the total for August and September is 813. This creates a skewed monthly distribution with more fires recorded prior to the month of July than after. This is consistent with other research reporting a greater frequency of fires in the spring (Clark, 1989).

Figure 5. Monthly Distribution of Lightning-Caused Forest Fires



It is apparent from the graph that the four years with the largest number of fires, 1983, 1988, 1989, and 1991 are the result of at least two months of intense burning, with the number of fires for these months being well above the monthly means.

All of the years with a high number of fires, over 400/year, had an above average June and three of four had an above average July. In 1983, July experienced 71 fires with a mean of 93, June, 239 fires with a mean of 68 and August, 144 fires with a mean of 46.

The years with the maximum number of fires, contain three of the five highest monthly values for number of forest fires for the months: June 1983 (239), August 1983 (144) and July 1988 (263). The May high, 1986 (74), and the September high, 1990 (72), are not of a great enough magnitude to significantly influence the annual lightning-caused fire total unless paired with other high monthly values. In the case of the May high the number of fires for the year is still below the annual mean.

In 1983, which has the maximum number of fires (485), all fire months, with the exception of May (0), experience above average numbers of fires, with the maximum number in June (239). The patterns for 1988 and 1989 are very similar, with peaks in July (250, 263), secondary maximums in June (126, 134), and an above average August (89).

In 1991, June (225 mean 63), July (157 mean 93), and August (89 and mean 46), all have above average numbers of lightning-caused forest fires. All of the high fire years have an above average June value and three out of four have an above average July incidence.

There are other months with extreme values, August 1981 (89), May 1986 (74, mean 17), September 1990 (72, mean 8) and July 1990 (111), but these are all tempered by lower than normal June values. In 1981, there were only eleven June fires; in 1986 four, and in 1990 only nineteen recorded.

The monthly fire number peaks in July for the most part, with June having the occasional peak in the distribution. This occurs four times in the distribution in the years 1982, 1983, 1991 and 1992. In the years with a low number of fires (1979, 1984, 1986, 1987) July is always the peak fire month.

Other months in the fire season may have a fire average that is high but if June is low another monthly high will not be sufficient to influence the yearly mean. Examples of this are September (mean eight) in 1990 experienced 72 fires, yet the yearly total was 257. In June, 1990, only nineteen lightning-caused fires occurred, for the same year July had 111 fires while its monthly average was 93. May, 1986, had 74 fires but June had 4, July 19 and August 11. This was a very high number of lightning-caused forest fires for May (mean 17) yet it has little influence on the yearly average.

The months of May and September may have very high numbers of fires, as in 1986 and 1990, but these numbers are not sufficient to sway the distribution total. In fact there was no instance where a high number of fires in May was followed by a high annual total. Therefore, fires in the spring and fall do not necessarily foreshadow or follow a season fraught with lightning-caused fires. These two months are highest in the low years and remain near the mean in high years.

For two of the years with the highest number of fires 1983 (485), 1991 (478), June also had two of its highest fire counts 239 and 225, respectively. For other June records the number is only twice above 100 fires, in 1988 (126), annual total 440 and 1989 (134), annual total 468. In every year that the number of fires in June surpassed the monthly average (68) it was a severe fire year. It appears that if June has more than 64 fires it is going to be a high fire year.

July has over 200 fires only twice during the record, in 1988 (250) and 1989 (263). As in June, again there are only two years with over 100 fires, 1990 (111), and 1991 (157); only 1991 was a high fire year. It is possible for the number of fires in July to surpass the monthly average and still have a low fire year. Although July has more fires in this fifteen year period, June is the more important month in predicting the severity of the fire season.

August exceeds 100 fires only once during 1983 (144). In 1988, another high year the number of fires in August (36) was below the August monthly mean of 46. There are only two remarkable years for September burnings, 1990 (72), annual total 257, and 1983 (31), annual total 485.

With the exception of May 1986 (74), all of the months in the four years with the fewest fires are below average in number of lightning-caused forest fires.

A comparison for each months high and low fire values, reveals a large range in the monthly number of fires during the study period. The monthly highs and lows, taken from Table 2. Annual and Monthly Distribution of Lightning, 1978-1992, are:

May, 0 and 74;

June 4 and 239;

July 16 and 263;

August 8 and 144; and

September 0 and 72.

The range is greatest for the month of July (247) with June (235) second. The range of the number of fires at the beginning and end of the fire season (May (74) - September (72)) is remarkably similar.

There are many more below average values for each month than above average values;

for the May record nine years are below average and six above;

June, eleven below, four above;

July, nine below and six above;

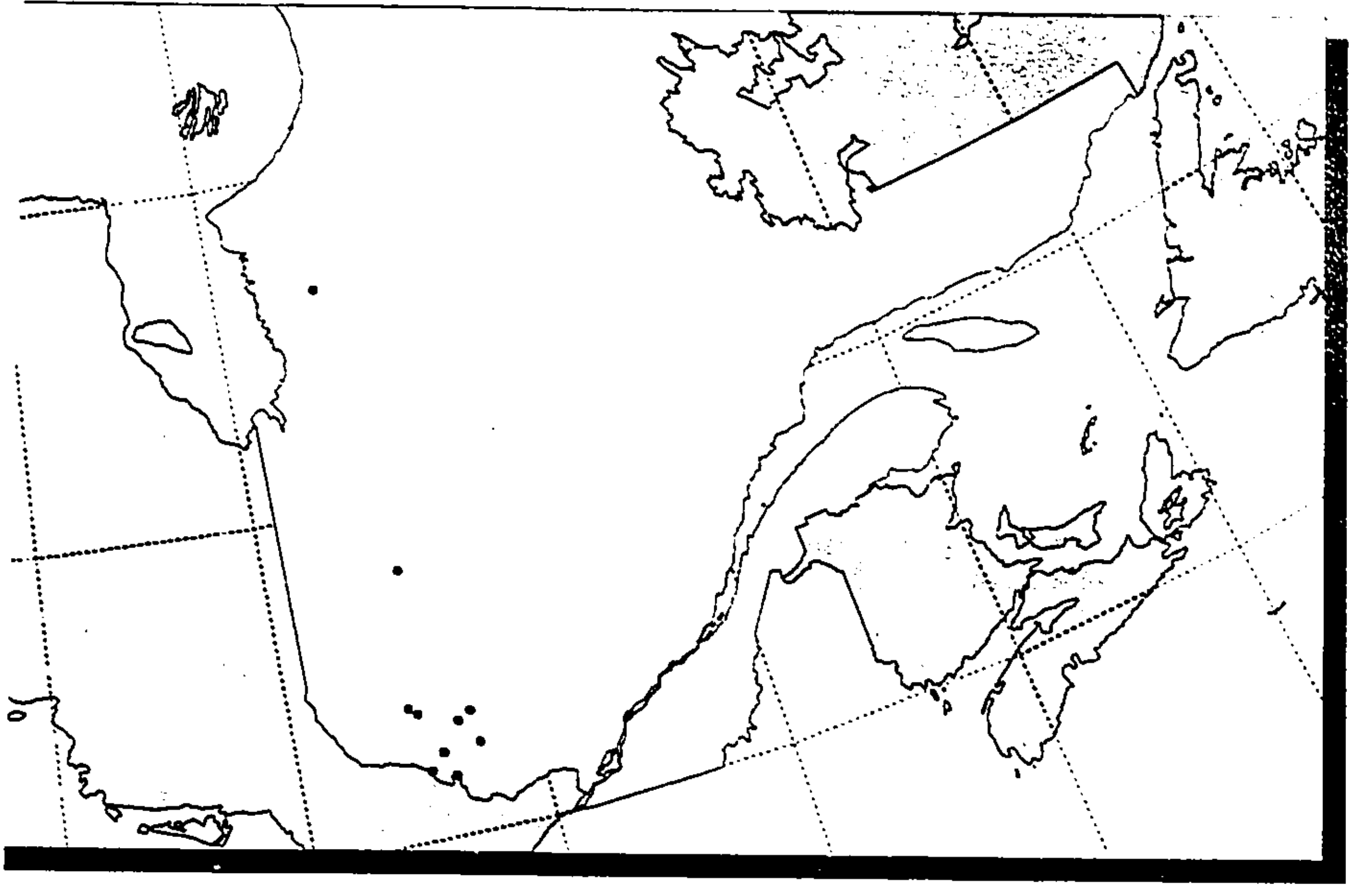
August, ten below and five above the mean;

and September has only two monthly records above the mean. Correspondingly, ten years of the fifteen-year record, are below the annual average. Fires are much less frequent than the means and totals imply with a few deviant months raising the annual sums and means.

4.7.2 Monthly Spatial Pattern

The spatial distribution of lightning-caused forest fires for each of the fire months is shown on the following maps. Here, the total number of lightning-caused fires are mapped for each month and presented with a frequency graph for that month.

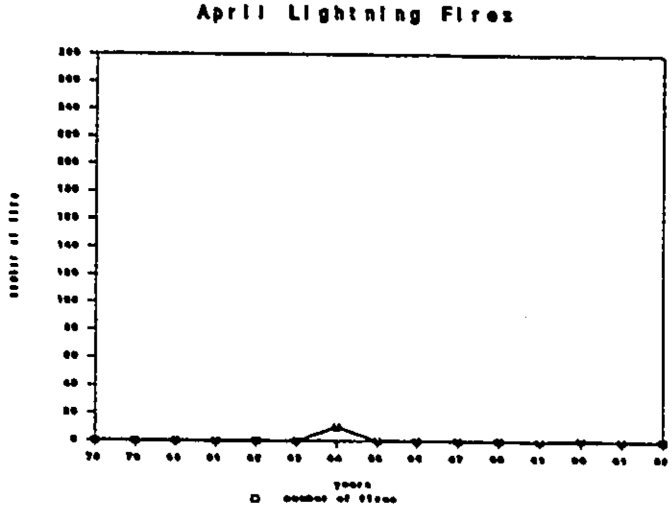
Map 6. Lightning Fires, April 1978 - 1992



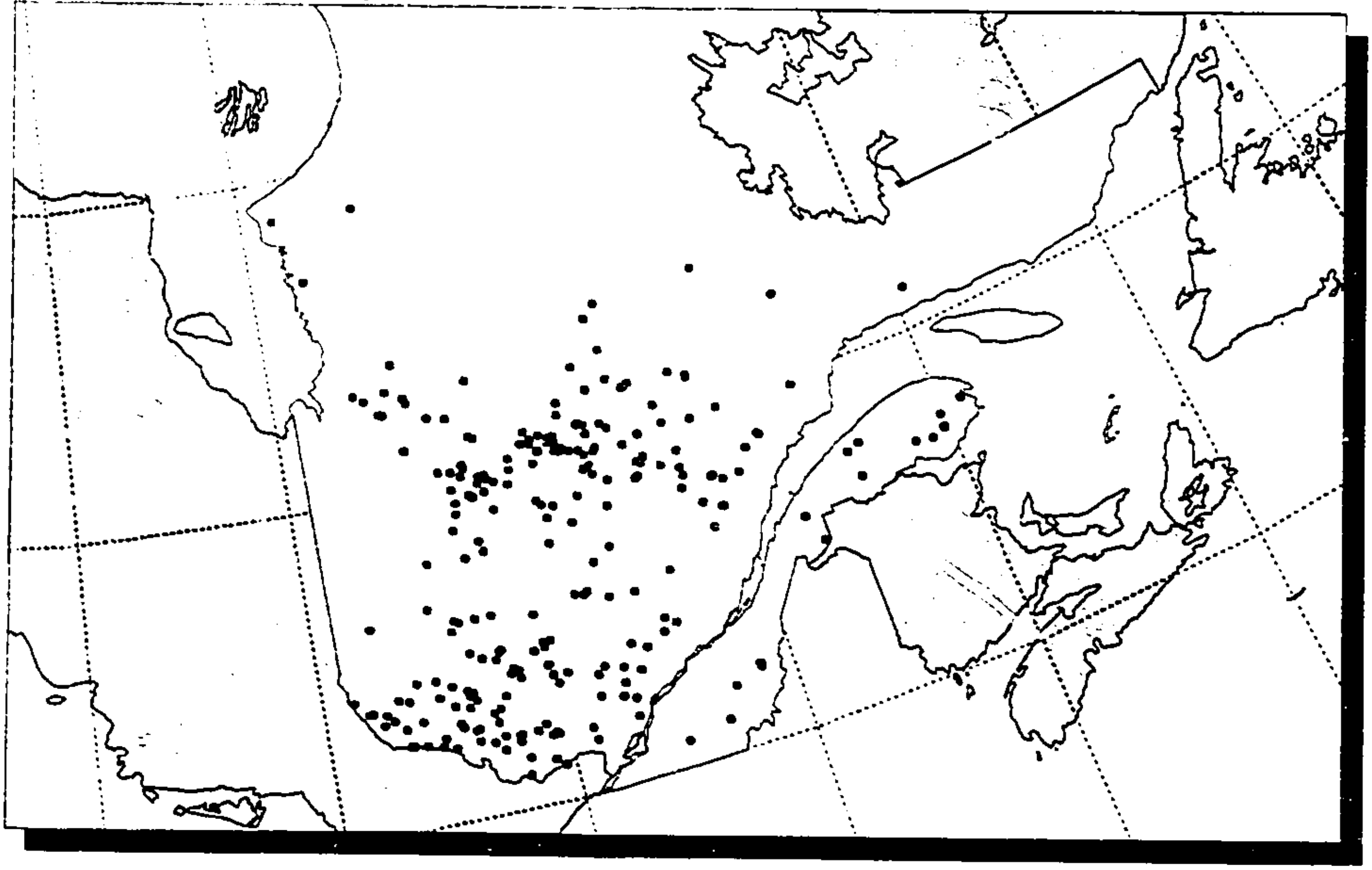
scale 5 cm = 618 km

Figure 6. April (11): All fires with the exception of two are located in the southwest portion of the province in the maple basswood zone

All but one fire (1990) occurs in 1984.

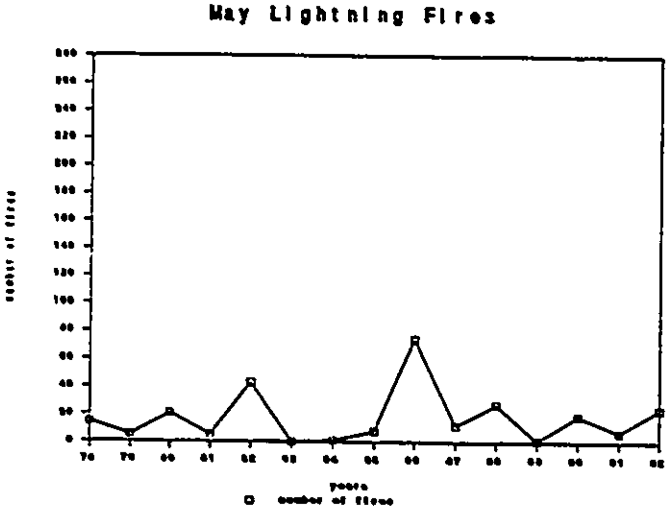


Map 7. Lightning Fires, May 1978 - 1992

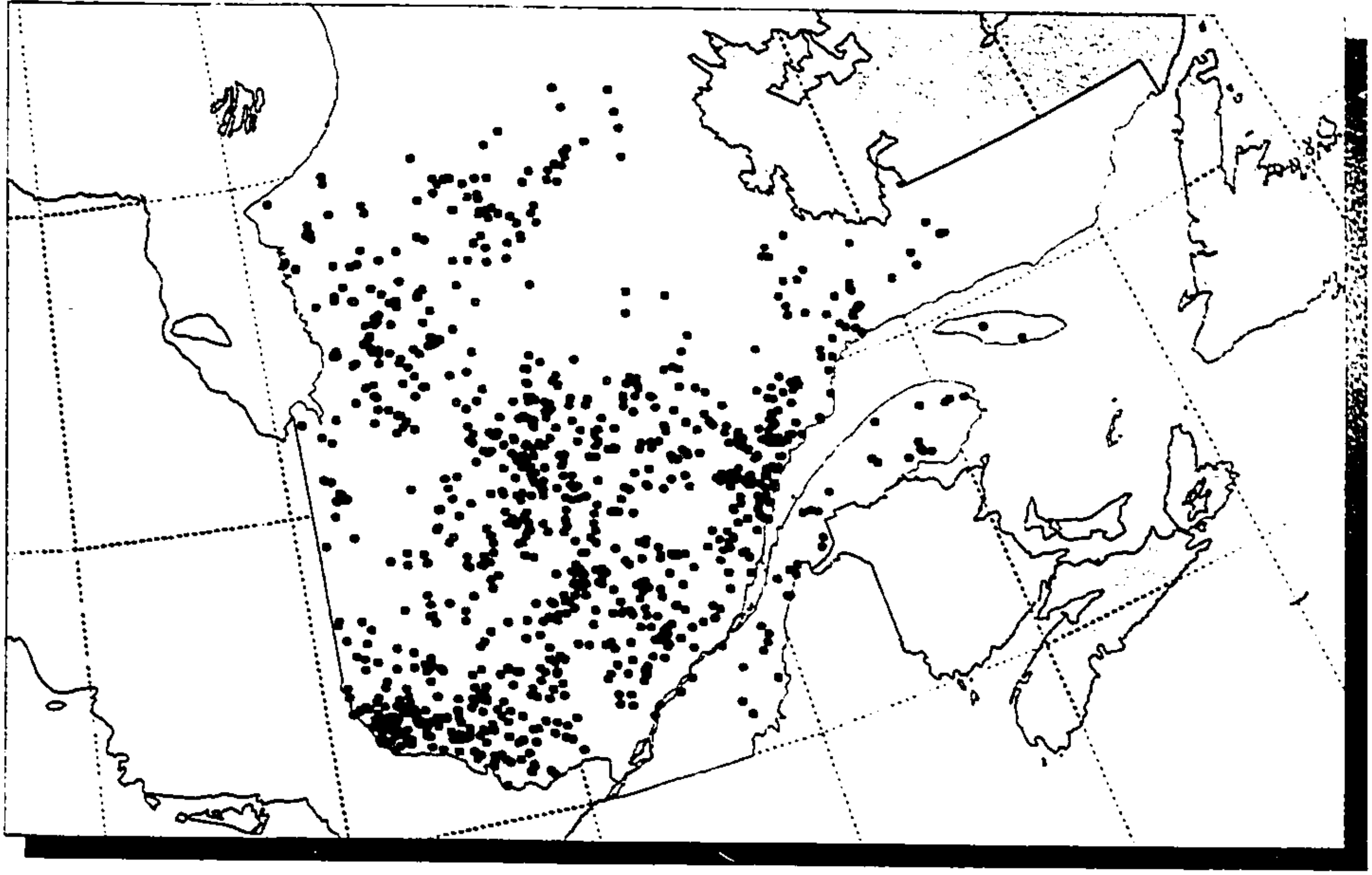


scale 5 cm = 618 km

Figure 7. May (262): The pattern is diagonal across the province from south-west to north-east. Few fires occur north of 55° north latitude and 28 % of all May fires occur in 1986.



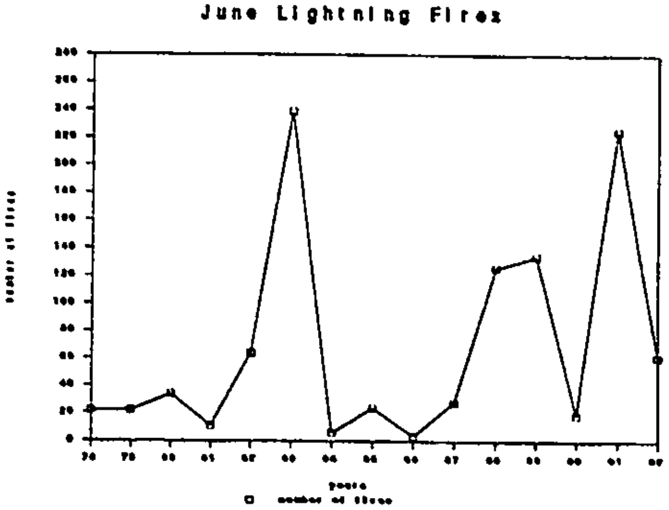
Map 8. Lightning Fires, June 1978 - 1992



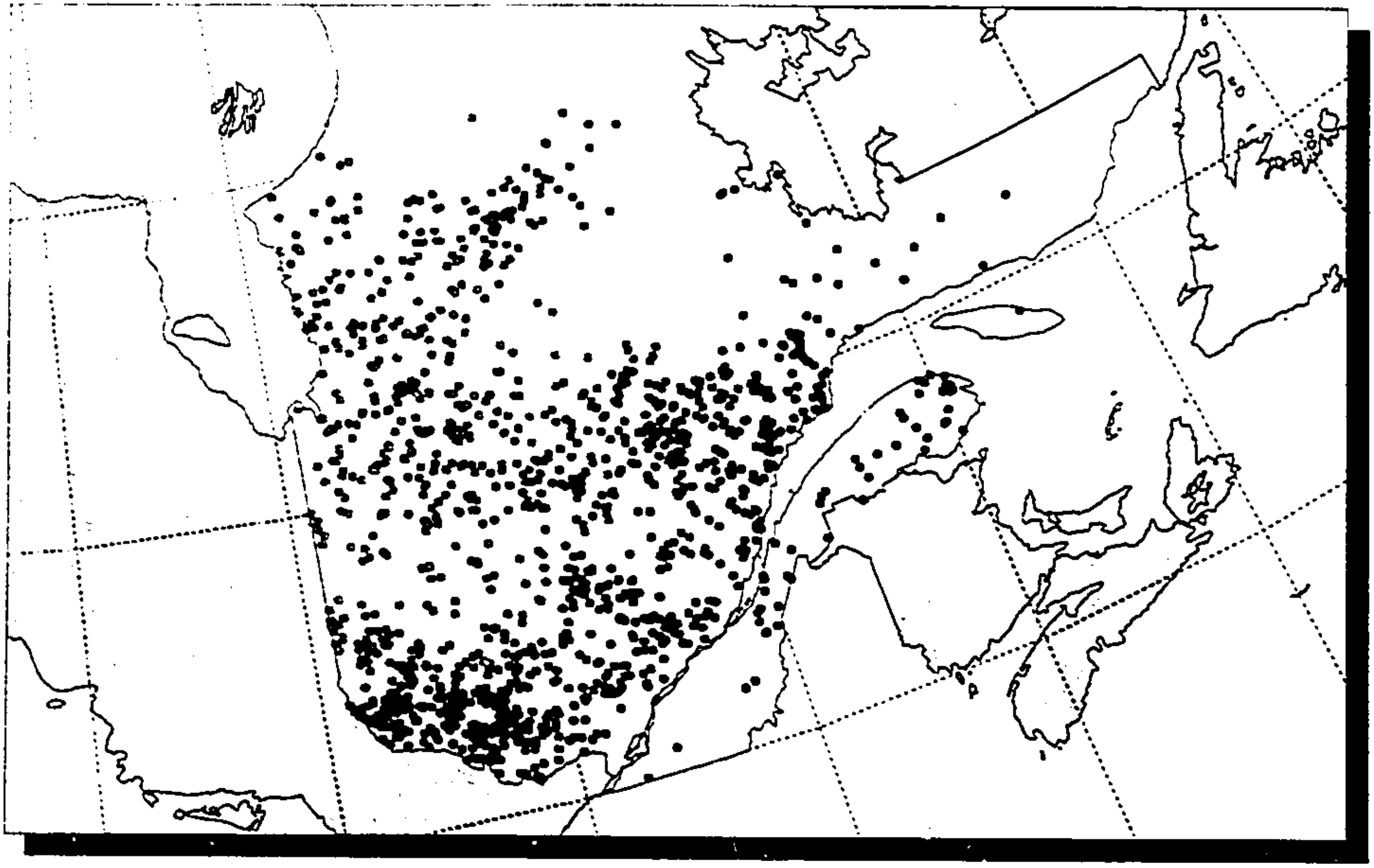
scale 5 cm = 618 km

Figure 8. June (1019): The increased number of fires in June cover most of the study area.

71 % of all June fires occur in the four years, 1983, 1988, 1989 and 1991.



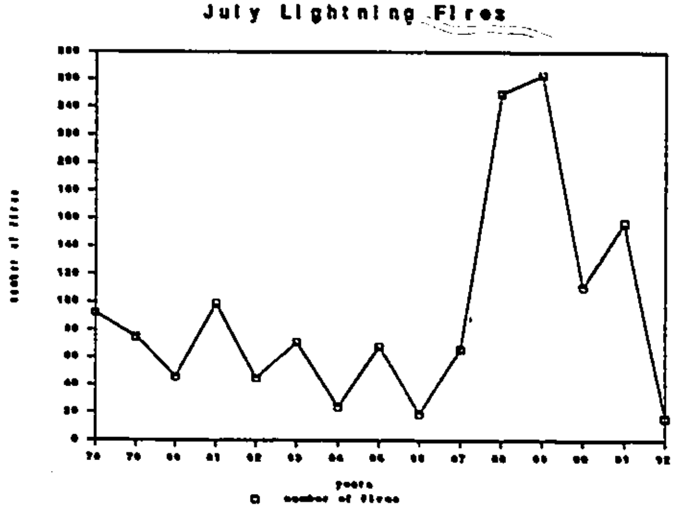
Map 9. Lightning Fires, July 1978 - 1992



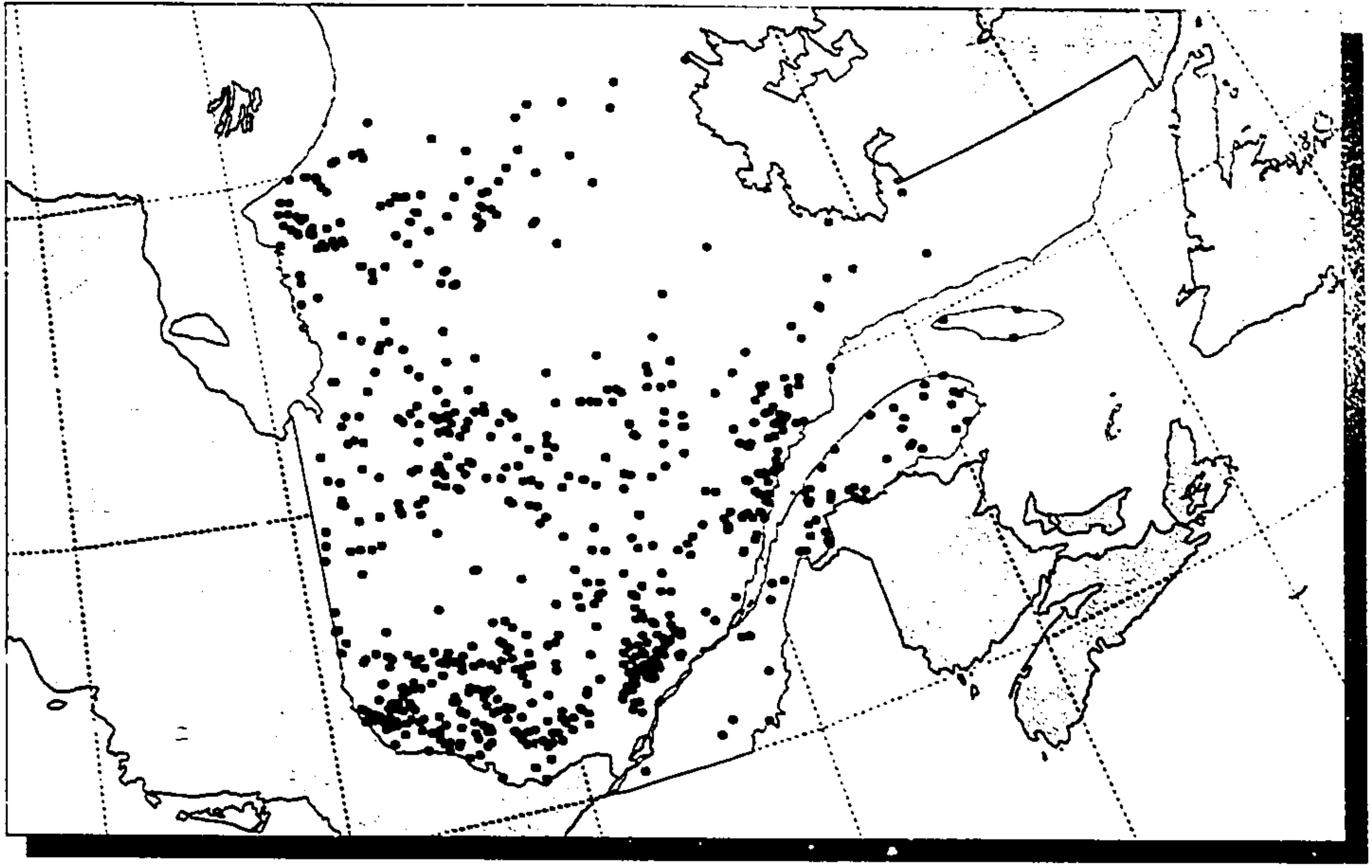
scale 5 cm = 618 km

Figure 9. July (1402): The three maximums are apparent and the concentration in the southwest reaches its peak.

There are clearly two temporal patterns, prior to 1988, mean of 60.5 and after 1987 mean 199.25.



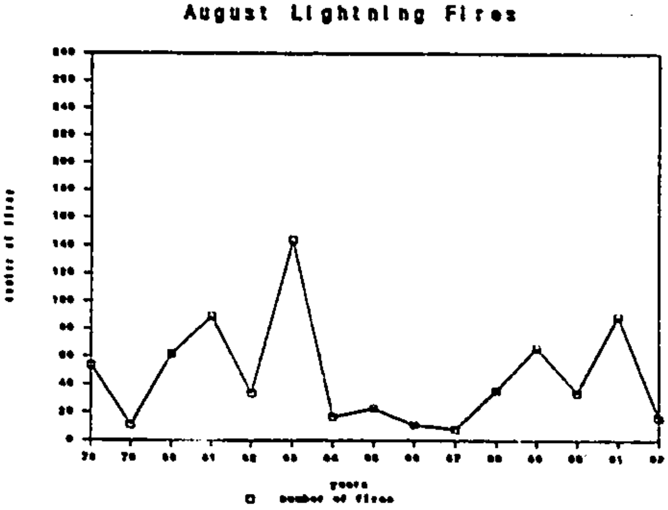
Map 10. Lightning Fires, August 1978 - 1992



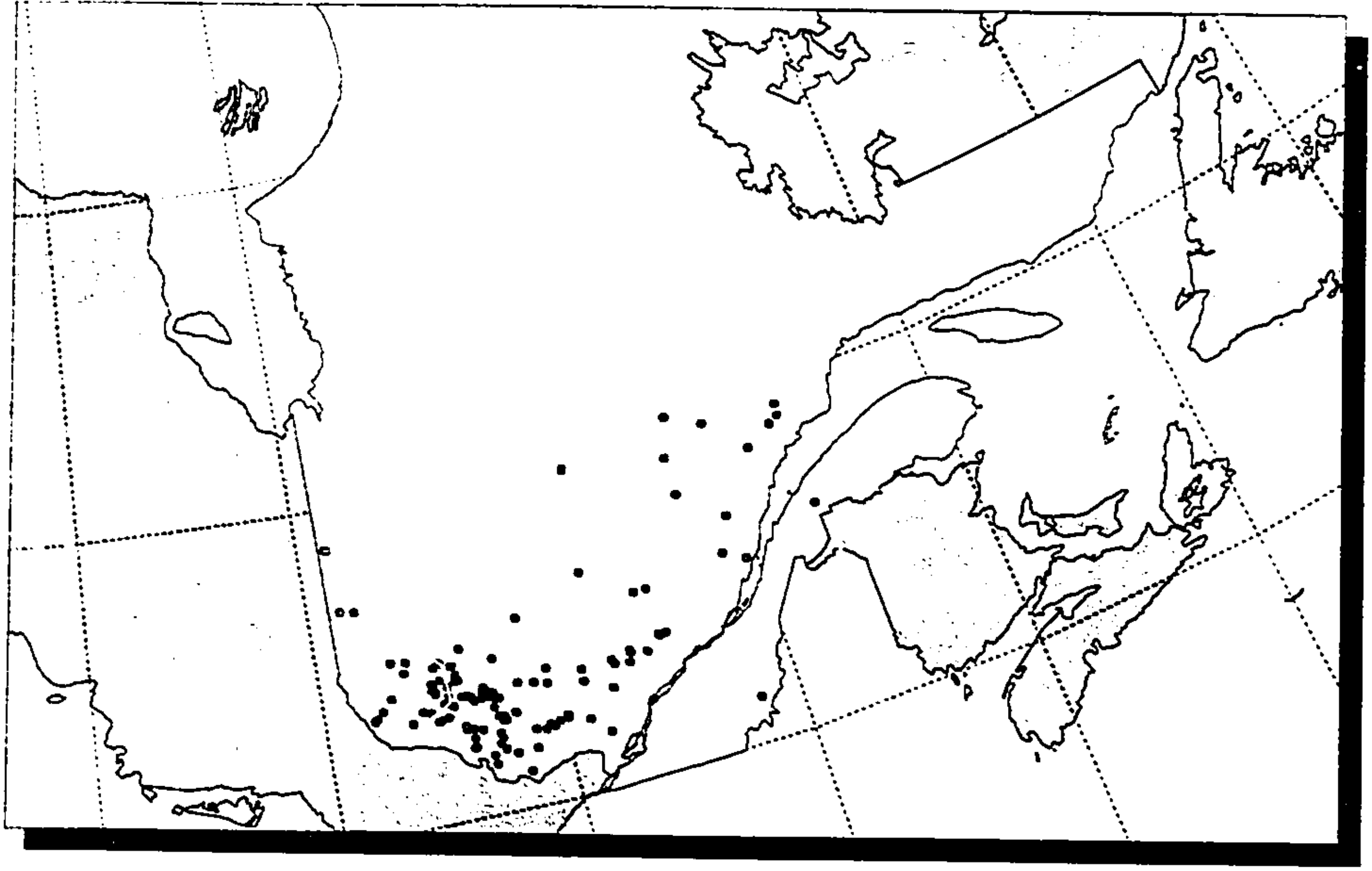
scale 5 cm = 618 km

Figure 10. August (694): The three bands are apparent, as is the trend along the St. Lawrence River.

41 % of August fires occur in three years, 1983, 1981 and 1991.

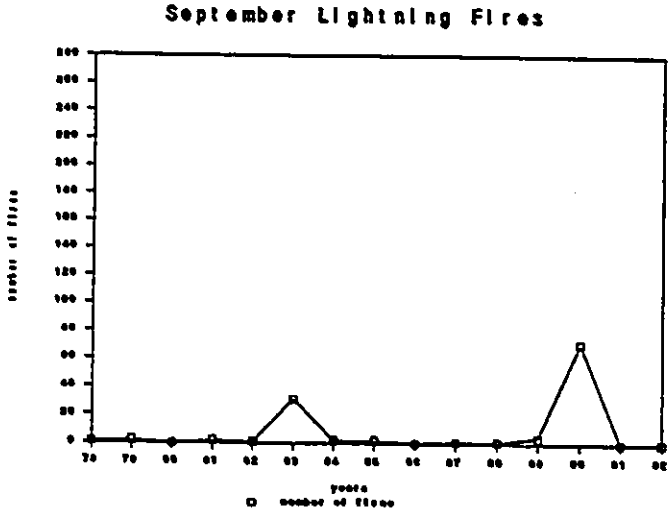


Map 11. Lightning Fires, September 1978 - 1992



scale 5 cm = 618 km

Figure 11. September (119): Most September fires occur in the south-west and along the north shore. There are no fires north of 50° north latitude 87 % of the fires occur in two years, mean 51.5. The mean for all other years is 1.23



The spatial predominance of fires varies by month. Generally, the southern regions of the province experience fires only in the months of April and May, while in June the distribution is spatially at its most random.

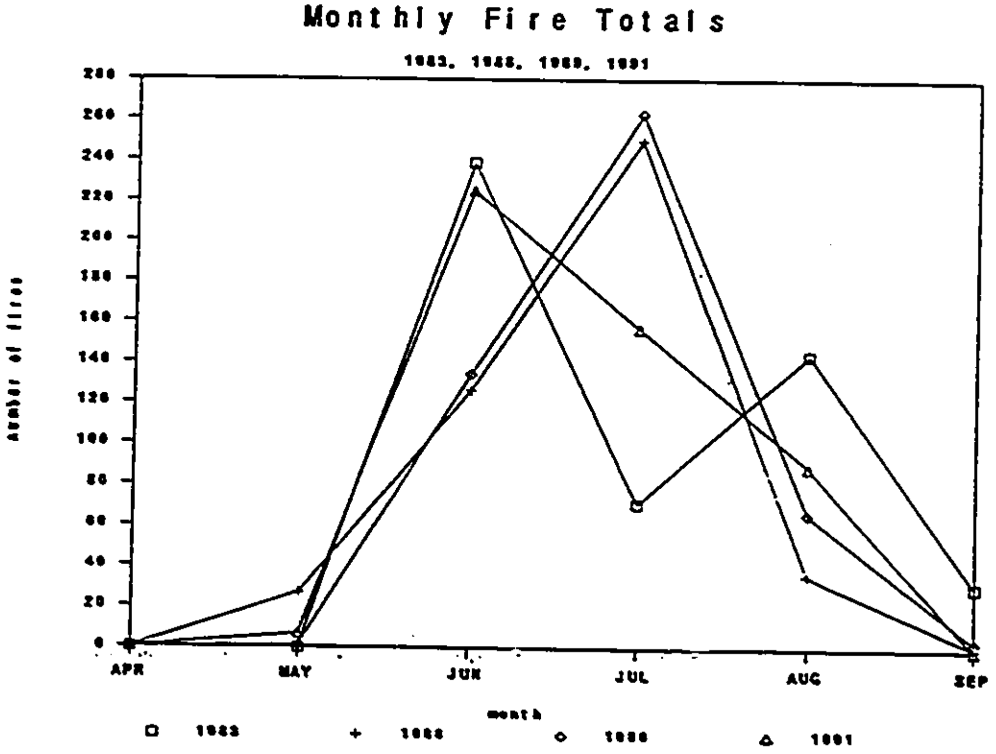
May fires appear as two clusters, mid-province and south-west corner, while September fires are concentrated in the south-west region of the province. The absence of fires in May and September in more northerly latitudes is probably a function of snow-melt in the spring and increased precipitation in the fall.

4.8 Comparison of High and Low Number Fire Months

The eight years presented on Map 5. Comparison of High and Low Fire Years are now analysed at a monthly interval.

The monthly fire totals for the years with the greatest number of fires (1983, 1988, 1989, 1991) display more variability than the comparable graph for years with the lowest number of fires (1978, 1984, 1986, 1987). The four years with the fewest number of fires always have the peak number of fires in July.

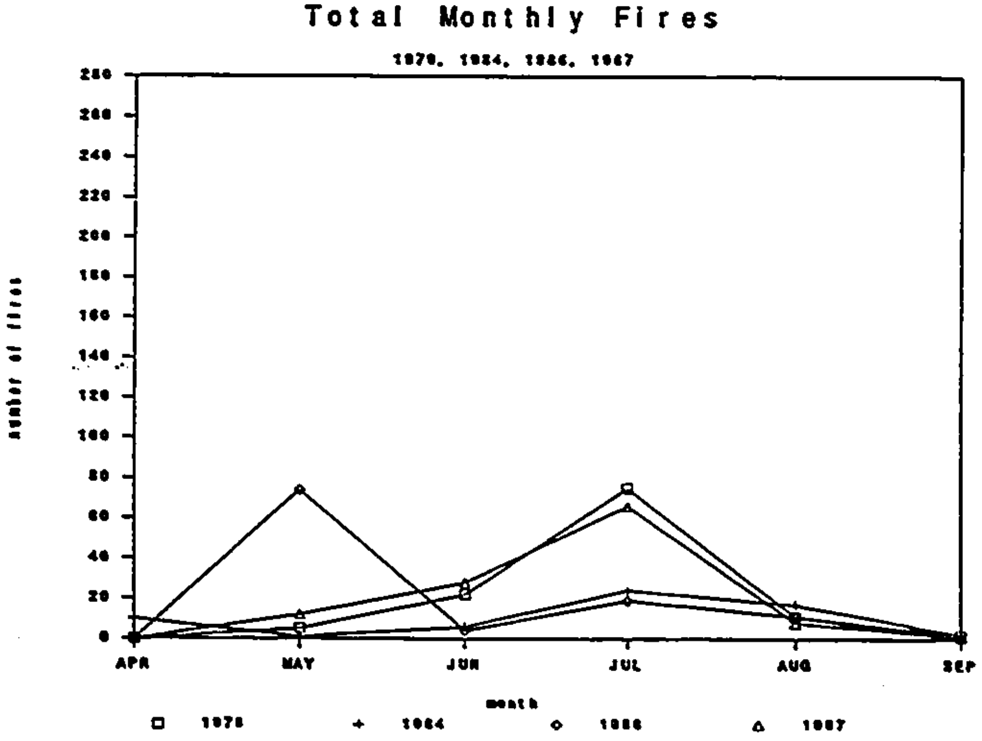
Figure 12. Monthly Lightning-Caused Fires for the Four Years with the Greatest Number of Fires



July has the greatest number of fires for the four years totalling 741. When the peak in the number of lightning-caused fires is in June, it is never as high as a July peak. The peak for the number of fires is in either June (1983, 1991) or July (1988, 1989). The total number of fires for June is 724.

There is little variation in the records for the month of May with a range of eight, while August displays much more variability with a range of 108 fires between 1983 and 1988.

Figure 13. Monthly Lightning-Caused Fires for the Four Years with the Least Number of Fires



July is the peak month for lightning-caused forest fires for the four years with the fewest fires, three of the four years. The incongruous record, May 1986, unusual regardless of high or low year. The total number of fires in July is 181 and for June 117.

Not-with-standing the overall greater number of fires in the high and low graphs, they remain similar in form. July usually has the majority of fires for the study area, and June is often the second highest in the distribution. August and September are more important contributors to the number of fires in the years with more fires and April and May are more important during the years with fewer fires.

4.9 Weather Variables

The weather data from Environment Canada are presented for two time periods: the data are aggregated first to create an overall picture of the fifteen year study period, and then the monthly data are presented in greater depth using data derived from a sample of five weather stations. The fifteen years of precipitation data are aggregated to create a map of isohyets for the 1978 - 1992 fire seasons. Similarly, a map of isotherms is created for fire season average temperatures and finally a map of the total number of days with thunderstorms is created.

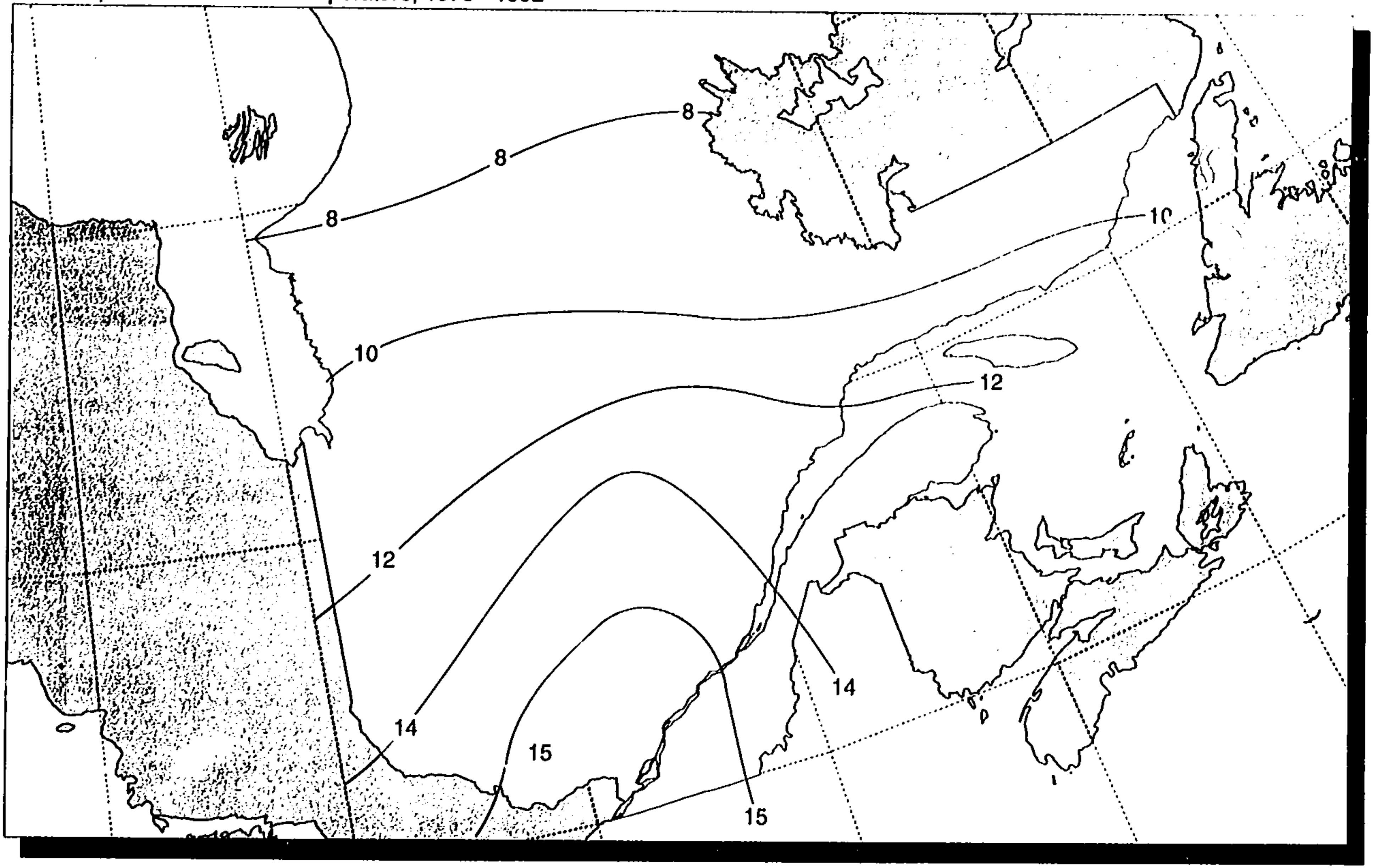
Snowfall, important to the annual water balance, is not critical to research on lightning ignitions. The vast majority of fires occur during the mid-summer months when snow is absent from the landscape. If lightning strikes while snow is present it serves to limit fire spread by providing a ready source of H_2O. The presence of snow has a far greater effect on fire spread than on lightning-ignition.

4.9.1 Temperature

The temperatures recorded by the Environment Canada Weather Stations are averaged for the six fire months (April - September inclusive) for the period of the record. The data shown on Map 12. Mean Fire Season Temperature, 1978 - 1992 are the fire season average temperatures from each weather station.

The map predictably shows a drop in mean summer temperature from south to north. The temperature gradient increases with latitude. The infiltration of warm southern air pushes the isotherms northward in the south central region. By 50° north latitude, the effect on the south central infiltration is no longer present. The drop in temperature coincides with areas recording the drop in fires from south to north, and areas experiencing the greatest number of fires coincides with the highest temperatures.

Map 12. Fire Season Temperature, 1978 - 1992



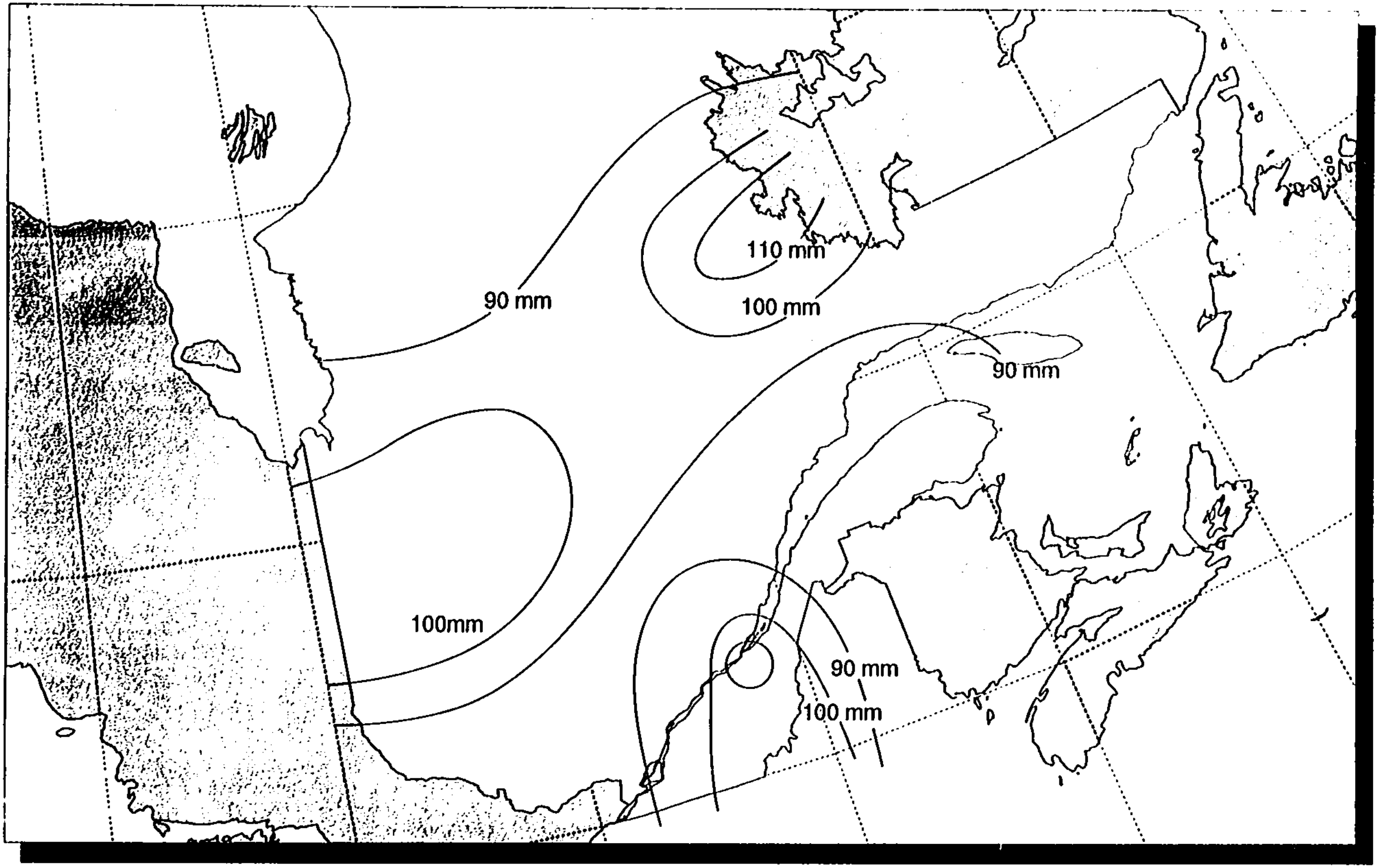
scale 5 cm = 448 km

4.9.2 Precipitation

Precipitation data are obtained from the same stations as for temperature data, see Appendix II. Isohyets are created from mean annual summer precipitation, calculated as for temperature.

Map 13. Mean Fire Season Precipitation 1978-1992 shows a northward tilting pattern, from west to east. Three areas of high precipitation are apparent. These centre on 50° 05' north latitude, 76° west longitude; 46° 9' north latitude, 71° west longitude; and 52° north latitude, 68° west longitude. Precipitation decreases steadily northward of the two northern high centres. Between the two northern highs and the southern most high is a trough. The area with a fire season average of less than 80 mm of rain coincides with the region experiencing the highest number of fires occur. Both the area to the south of James Bay, the northeast section and the south shore, including 70° west longitude to 73° west longitude and 45° north latitude to 48° north latitude of the study area, are areas of minimal burning, experiencing precipitation in excess of 100 mm per fire season. The northern 90 mm isohyet marks a return to an increased number of fires.

Map 13 Fire Season Precipitation, 1978 - 1992



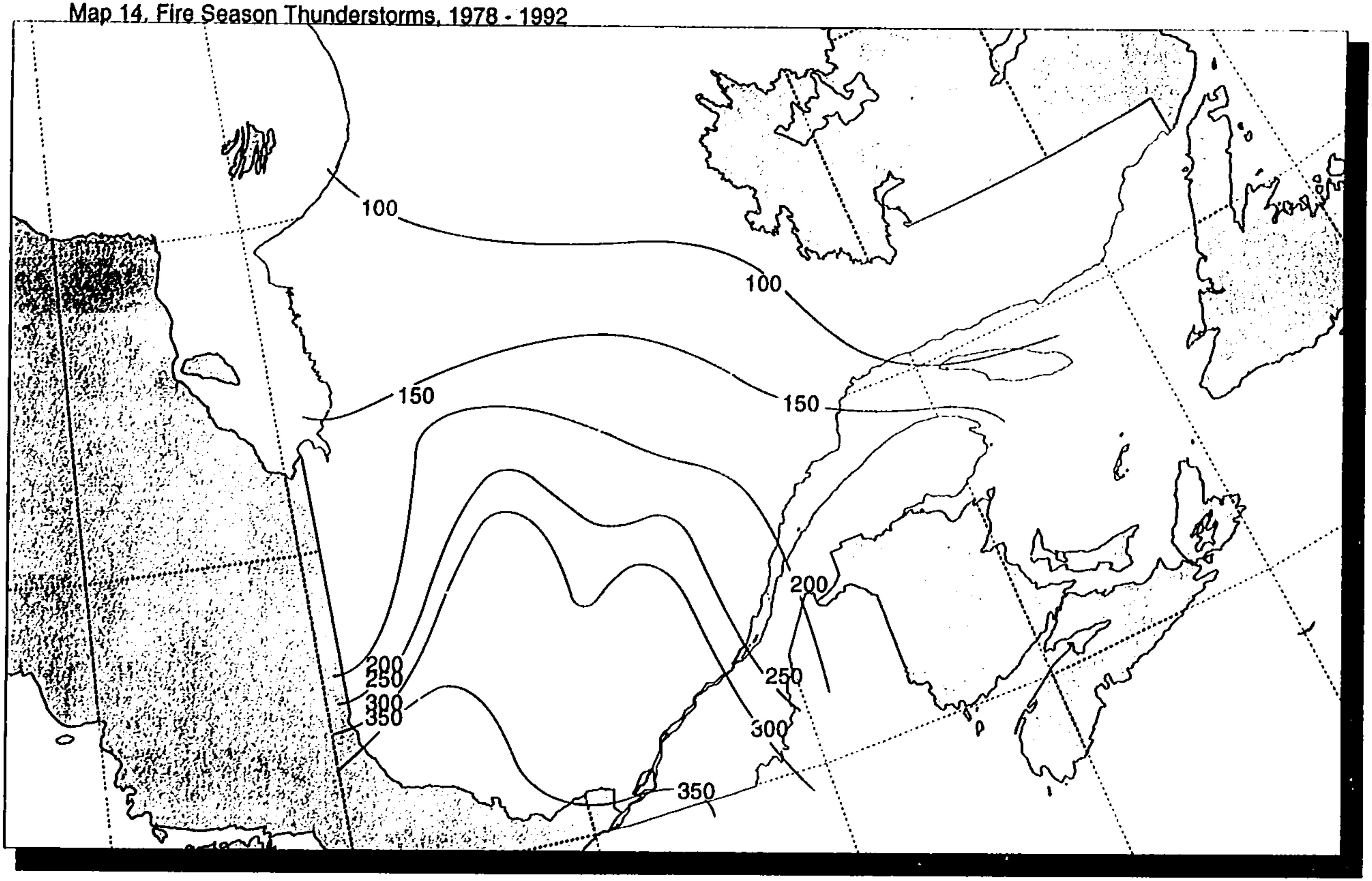
scale 5 cm = 448 km

4.9.3 Thunderstorms

Thunderstorm data are available from the same set of weather stations as temperature and precipitation, with the exception of Gagnon. The number of days with thunderstorms increases along a trajectory similar to that of precipitation. The number of stormy days increases pushing from the southwest to northeast, with the maximum located in the southwest portion of the province. The greatest number of days with thunderstorms, for the study period, is at Ottawa - Hull (359), with Senneterre second (353).

The highs for the total number of stormy days coincides with the southeast region of lightning-caused fire maximums. The increase in the number of days with storms along the north shore coincides with the fire pattern of increased burning. Again there is a match in the decrease from south to north, and as storms decrease so do fires.

Map 14. Fire Season Thunderstorms, 1978 - 1992



scale 5 cm = 448 km

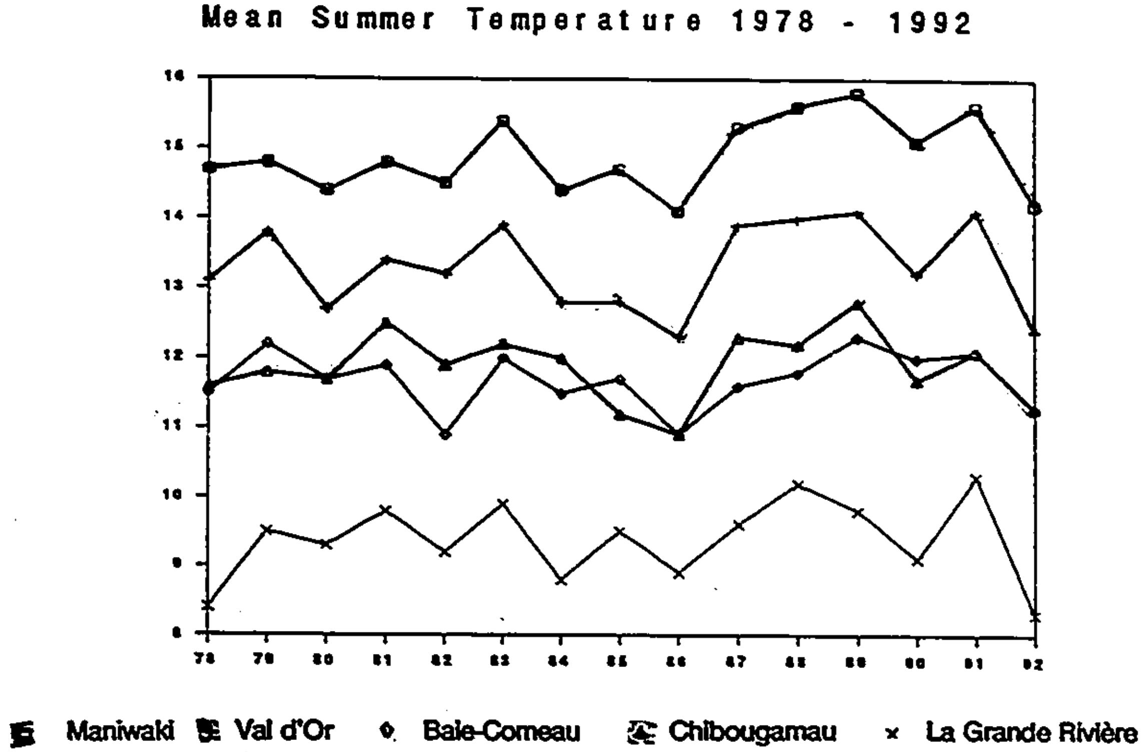
4.10 Weather Summary by Month

Annual and monthly weather data for a sample of five representative stations are used to assess changes in temperature, precipitation and thunderstorm occurrence, in more detail. The five stations are selected from across the province; Maniwaki, in the southeast, an area with a very high number of forest fires; Val d' Or, in the western portion of the province and with a low number of fires; Baie-Comeau, located in the northeastern portion of the study area on the St. Lawrence River with a relatively high number of fires; Chibougamau, in the north central portion of the study area and experiences a high number of fires; and finally La Grande Rivière, in the northeast of the study area (see Appendix II, Map 15. Environment Canada Weather Stations).

The three weather variables are presented with the means for the fire seasons for each fire station. Fire season, April to September, averages are graphed and anomalies between stations are investigated to determine their effect on the location of lightning-caused fires.

4.10.1 Temperature

Figure 14. Mean Summer Temperature, April - September, for Selected Stations, 1978-1992



The temperature gradient from north to south is a dominant feature of the graph. The more southerly station, Maniwaki, having the warmest temperatures and the more northerly, La Grande Rivière, the coldest. The stations at

Baie-Comeau and Chibougamau show similar temperature patterns, weaving past each other throughout the record.

In the later part of the eighties there is a warming trend in the study area. This is also when three of the four (1988, 1989, 1991) highest number of annual forest fire records occur. All years experiencing a large number of fires (1983, 1988, 1989, 1991) recorded above average temperatures.

Generally, the stations follow similar patterns for warming and cooling; however occasionally one station varies from the others. These anomalies for temperatures are:

1985: all stations record increased mean summer temperatures from the previous year, except Chibougamau;

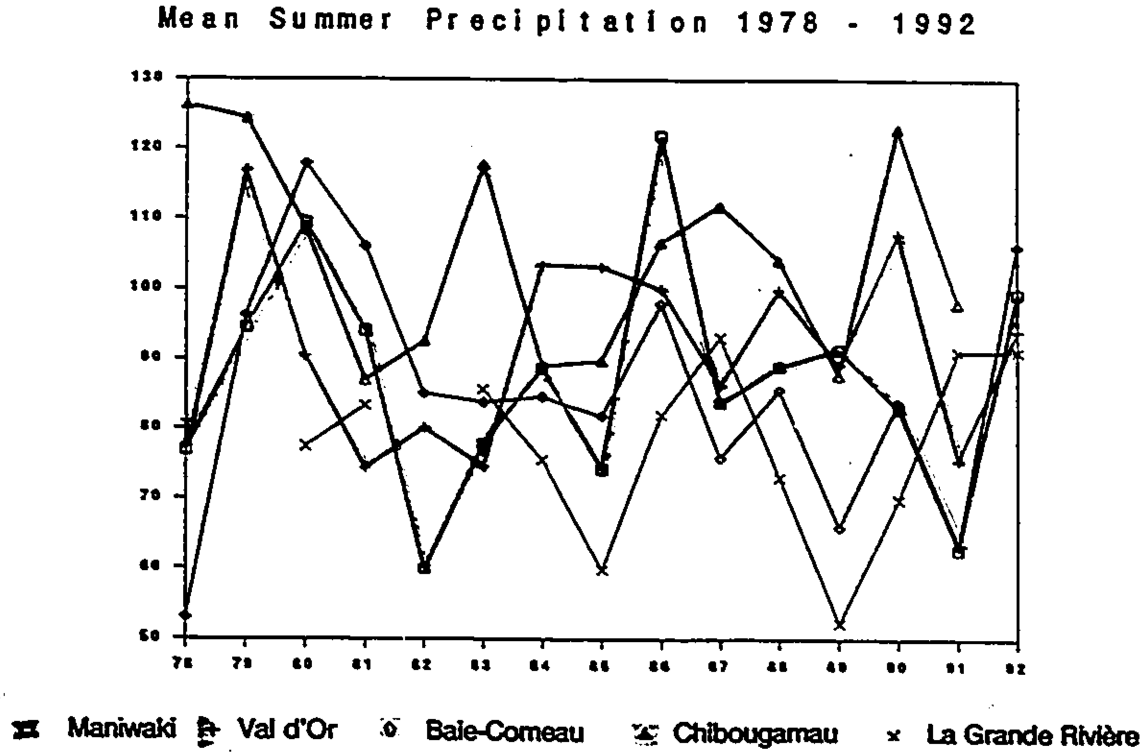
1988: all stations record an increase except Chibougamau and Baie-Comeau;

1989: all stations increase except La Grande; and

1991: all stations increase except for Baie-Comeau.

4.10.2 Precipitation

Figure 15. Mean Summer Precipitation, April - September, for Selected Stations, 1978-1992



The data for rainfall display much more variability than temperature data. Figure 15. reveals an association between years of low rainfall and increased burning (1983, 1988, 1989, 1990) and decreased burning in years with greater precipitation (1978, 1984, 1986, 1987).

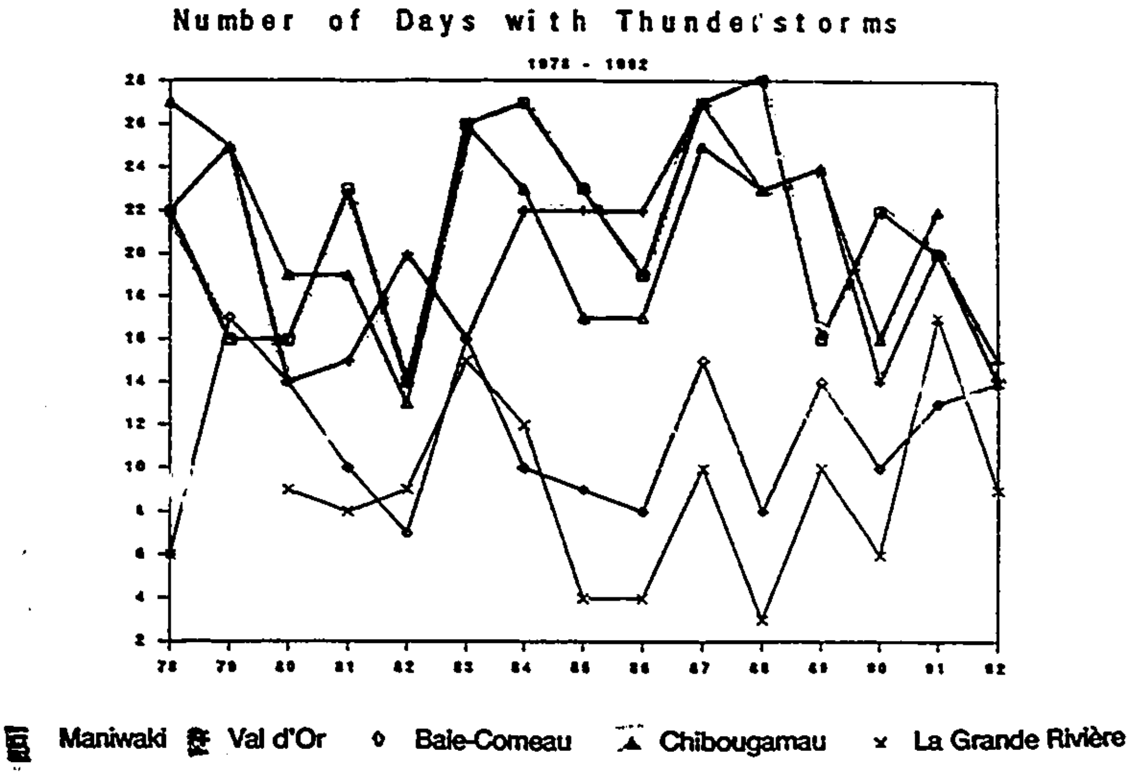
Excepting Val d'Or, 1984, and Chibougamau, 1983, there is little difference in the precipitation patterns of 1983, the year with the greatest numbers of storms, and 1984, the year with the fewest number of storms.

The years 1991 and 1989 are clearly drier than both preceding and subsequent years; whereas in 1983, Chibougamau had a wet season and all other weather stations in the sample recorded average amounts of rainfall.

The years 1979, 1986 and 1992 experienced much precipitation and a low number of fires 115, 108, and 117 respectively.

4.10.3 Thunderstorms

Figure 16. Number of Days with Thunderstorms, April - September, for Selected Stations, 1978-1992



The graph for number of days with thunderstorms reveals two divergent weather patterns for the stations La Grande and Baie-Comeau, and Maniwaki, Chibougamau and Val d'Or. In the years 1984 to 1990 the three more northerly stations show an increase in the number of days with thunderstorms while the two southerly stations appear to have a decrease.

Generally, the patterns for the stations are similar usually rising and falling in tandem. Few stormy days occur in 1982, while 1983, 1984 and 1987 have a very large number of stormy days.

4.11 Temporal Comparison

The following section provides a comparison of the three weather variables in two ways: 1) the first ten years verses the last five years, and 2) the years with the greatest number of fires (1983, 1988, 1989, 1991) verses the years with the least number of fires (1978, 1984, 1986, 1987). The first comparison is tied to definite meteorological differences in the two time periods and the second is tied to the increased and decreased frequencies of lightning-caused forest fires.

Table 3. Comparison of Weather Variables, 1978 - 1987 verses 1988 - 1992

	Maniwaki	Val d'Or	Chibougamau	Baie-Comeau	La Grande Rivière
Mean Temperature					
78-87	14.7	13.13	11.83	11.57	9.29
88-92	15.24	14.12	12.02	11.9	9.54
difference	.56	.99	.19	.33	.25
Mean Precipitation					
78-87	90.15	90.55	105.41	88.25	78.57
88-92	85.07	93.32	96.48	88.04	75.45
difference	-5.08	2.77	-8.93	-.21	-3.12
Mean Stormy Days					
78-87	21.3	20.4	21.1	11.2	7.7
88-92	20	19.2	21.25	11.8	9
difference	-1.3	-1.2	.15	.6	1.3

average per fire season

Weather patterns for the stations are marked by an increase in temperature during the last five years of the record. The average temperature for the five stations for the first ten years of the record is 12.1°C and for the last five years 12.6°C. The greatest temperature difference was at Val d'Or where the mean temperature difference was .99°C between the average for the first ten years and last five years.

The precipitation and number of days with thunderstorms also presented a different pattern for these two periods. Precipitation dropped for all stations except Val d'Or. The precipitation average for the first ten years was 90.59 mm, while for the last five years the average was 87.62 mm, a difference of a mere 2.97 mm.

Again, for both of the comparisons, first ten years, last five years and high/low years, the number of days with thunderstorms decreased in the more southerly stations Maniwaki and Val d'Or and increased in Chibougamau, Baie-Comeau and La Grande Rivière. The difference in the number of storms increases with latitude for both of the sample periods. The minimum difference is .15 days for Chibougamau and the maximum is La Grande Rivière with a difference of 3.5 days.

The difference in the weather variables is more pronounced when the four years with the highest number of fires is presented along-side the four years with the lowest number of fires. The difference in the mean temperature for the annual sub-sets is .65 °C and precipitation drops from 97.89 mm for the years with few fires to a mean of 86.29 mm for the years with many fires, a difference of 11.6 mm of precipitation.

Table 4. Comparison of Weather Variables, 1979, 1984, 1986, 1987 verses 1984, 1988, 1989, 1991

	Maniwaki	Val d'Or	Chibougamau	Baie-Comeau	La Grande Rivière
Mean Temperature					
1979,84,86,87	14.65	13.2	11.73	12.8	9.2
1983,88,89,91	15.6	13.6	12.37	12.4	10.06
difference	.95	.40	.64	-.40	0.86
Mean Precipitation					
1979,84,86,87	97.25	101.6	108	88.67	83.5
1983,88,89,91	80.21	99.02	102	74.71	75.5
difference	-17.04	-2.58	-6.0	-13.96	-8.0
Mean Stormy Days					
1979,84,86,87	22.25	24	22.5	12.5	8.66
1983,88,89,91	22.5	20.75	23.75	12.75	11.25
difference	0.25	-3.25	1.25	0.25	-2.58

average per fire season

Consideration of the three variables in unison reveals deficits and surpluses for the various stations in relation to the other stations. These differences in the weather variables correspond to the changing locations of lightning-caused forest fires over the study period, for any given period of time.

When temperature records for a station do not follow the pattern established by companion stations, precipitation and thunderstorms are usually implicated as well. An excellent example of this is Chibougamau, 1983. All of the stations, with the exception of Chibougamau, show at least a half a degree increase in temperature while the increase for Chibougamau is less than .25 °C. Precipitation data reveals a substantial difference between this station and the others. In 1983, Chibougamau received over 115 mm of rain, while the other stations received less than 85 mm.

If we look to Map 21. Lightning Fires, 1983, it is apparent that Chibougamau had very few fires that year. In 1983, Chibougamau had a record twenty-six days with thunderstorms. This of course increases the opportunity for a lightning strike fire occurrence by providing a "match", but the accompanying precipitation likely reduced the ignobility of the fuel.

Maniwaki, also had many days with thunderstorms in 1983, twenty-six storms with the record being twenty-eight, in 1988, yet many fires still occurred in the southwest region. The difference between Maniwaki and Chibougamau is the amount of precipitation falling. Maniwaki had less than 80 mm, on average, in the five months.

In 1986, the Val d'Or weather station reports weather patterns which are anomalous with the other stations. Average precipitation drops compared to the previous year while all other stations experience an increase in precipitation.

The thunderstorm data does not reveal any difference for neither Val d'Or nor the other stations. Map 24. Lightning Fires, 1986, reflects this and fires are seen more to the north of the southwest maximum, in the Val d'Or area.

Chapter Five

Discussion

The following section brings together the data presented in Chapter Four. The relationship between the outbreak of lightning-caused forest fires is examined in relation to the study variables: species, species-age, temperature, precipitation and number of days with thunderstorms.

5.1 Temporal Variation of Lightning-Caused Forest Fires

The number of naturally-caused forest fires, occurring over the fifteen year study period, varies greatly from year to year. The number of fires ranges from a high of 483 in 1983 to a low of 60 the following year, 1984. Never-the-less the fifteen year record is easily divided into two distinct groups, the first ten years and the last five years or by groups of high and low fire number years. The mean number of fires for the first ten years was 174.8 and for the last five 352. The difference for the high and low comparison is even greater. The mean number of fires for the four years with the least number of fires is 99, while the mean for the four years with the greatest number of fires is 468.

Fires occur throughout the summer from April to September with the peak months for fire activity being June and July. For the four years with the most fires the increase in the number of lightning fires is usually the result of two months of intense burning, one of these months always being June. It would appear that if June has an above average number of fires this should serve as a warning of a severe fire year.

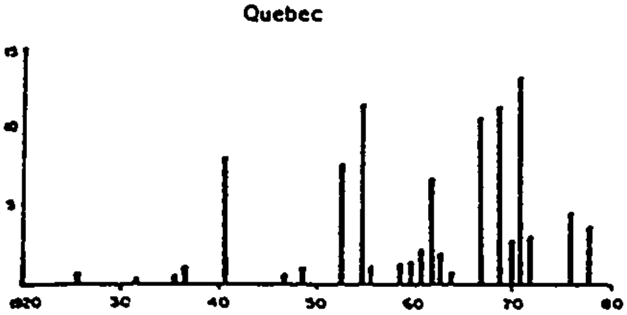
Spring fires do not occur often compared to the summer months. The number of lightning fires might be greater in the spring months were it not for green herbs and understorey vegetation. These are usually a deterrent to the spread of the fire in the early spring, and after greenup, because of their high moisture content, but they may contribute significantly to fire intensity and the rate of spread when in a dry condition (Chandler *et al.*,1983).

It should be kept in mind that determining the date of ignition of natural forest fires is not an easy task. The exact timing of the fire is not always transparent. Lightning may strike and ignite peat, dead snags, or duff and smoulder for long periods before igniting. This creates difficulties in temporally relating a storm to meteorological conditions (Komarek, Sr., 1966).

The frequency of natural forest fires in Québec is easily misrepresented when the fire number data are aggregated to create monthly or annual summaries. Fires are much less frequent than the means and totals imply with a few deviant months raising the annual sums and means. It is, of course the monthly variation in the number of fires that drives the annual variation in the number of fires.

Historically, forest fires may have been much less prevalent than these fifteen years of the study portray. In a study of the history and pattern of lightning-caused fires in southeastern Labrador D. Foster (1982) found that between the years 1870 and 1980 three decades (1890's, 1950's 1970's) account for approximately 70% of all of the area burned. Within each of the three decades Foster found one or two major fire years were usually followed by long periods of low fire incidence. The following figure of percentage area burned illustrates this point. Note the increase in latter half of the record.

Figure 17. Recent fire activity in Québec (Foster, 1982)



(the total area burned from 1923 - 1980 was calculated and the area burned during each year is presented as a percentage of this total)

Historical information on fire numbers is, for the most part, unobtainable so for the purposes of comparison fire number is related to area burned as these two variables are both considered to be indicators of severe fire years. Given this assumption, then Foster's work implies that the years with lower fire numbers are the more representative of "typical" fire behaviour in the province and the high fire number years are anomalous.

5.2 Spatial Distribution of Lightning-Caused Forest Fires

When all of the lightning-caused fires in the data record are mapped, see Map 4. Lightning Fires, 1978 -1992, distinct areas of fire absence and fire presence are seen. Generally, there is an overall zonal pattern when the distribution is regarded as a whole. When the study period is broken down and mapped by year and month the location of the forest fires changes within the confines of this overall distribution.

Given that the location of lightning-caused forest fires varies from month to month and year to year then within these time periods distinct patterns once again repeat throughout the record. The maps of the four years with few fires and four years with the greatest number of fires show essentially no variation of pattern. There were simply more fires in the latter distribution. The geographic pattern remains restricted to the same localities throughout the fire record and only occurrence and non-occurrence are then issues. This leads to the assumption that different variables drive the frequency and location of naturally-caused forest fires.

If we look to the study variable sets: weather and species, the only variable in the study experiencing minimal change is species distribution and species age. The meteorological variables are temporally and spatially dynamic. This dichotomy may explain the shifting forest fire pattern within it's geographic perimeter. The stable species related variables define the confines for the geographic location of natural fires while the dynamic meteorological variables dictate if a fire will or will not occur.

This assumption does not preclude an overlap or blending of these stable and dynamic factors. The link between forest species and weather conditions is firmly established (Heinselman 1981, Bryson 1966, 1970). Forest zones, areas that contain a distinct species groups such as the boreal forest, are largely shaped by the ambient climate which is unique to the area and necessary to the life within it. The effect of climate on biological survival was pointed out by Bryson (1966, 1970). He showed that climate regions defined by annual airstream dominance correspond well with many major biotic regions. This is due to the fact that *biota* developed under the prevailing conditions. This *climata/biota* match is less than perfect, tempered by microclimate and topographic factors. These modify the boundary to various extents.

The behaviour of forest fires is the result of complex processes that create a dynamic equilibrium among all of the elements (Van Wagner, 1983). Either, the absence of fuel or lightning will limit the opportunity for ignition and combustion. Ultimately, these fires depend on both the climate and the rate at which potential fuels accumulate following each fire (Van Wagner, 1983).

The intermingling of climate and forest species is apparent in eastern and central Canada where the climate becomes drier from east to west and this trend is evident in the fire frequency record. This trend is also apparent in the composition of the boreal forest as balsam fir and black spruce increase eastwards and jack pine and trembling aspen increase toward the west (Rowe & Scotter, 1973). Therefore, the change in fire frequency is also coincident with species change.

The greatest concentration of fire is in the deciduous and mixed forest of southwest Québec. The North Shore, another area of high fire numbers, is dominated by spruce, while the third area of increased fire frequency in the north is composed mostly of spruce and taiga.

A visual coincidence of forest age and number of fires is apparent when the two coverages, forest age and the total distribution of lightning-caused forest fires, are overlaid. Map 4. Forest Age, demonstrates that forest age was an important factor in determining the spatial preference of lightning-caused forest fires for this area of Québec, during the period 1978 - 1992. Chandler *et al.*,1983, proposed that as the age of a stand increases so too does the likelihood of forest fires. This correlation in forest age and increased number of fires is predicted as a function of fuel loading. The calculation for fuel loading is dependent on the age of the stand and is independent of the vegetation type, for more information on fuel loading refer to pages 21 and 22. Fire occurrence did match well with forest age except in the north where fires continue to occur in tracts of land that are largely burned off.

Foster (1982) found in Labrador that the occurrence of fire was patchy and that its distribution was preferential toward young forests that offered an open matrix for the spread of fire and the drying of forest fines. This may account for the prevalence of fire in the decimated landscapes of the north. The burgeoning conifer landscapes of the north may be more susceptible to natural fire and this would help explain the presence of fire in the north in every year of the study.

Van Wagner, 1983, cautions that fire behaviour in the boreal forest is not a simple function of age. He found that "...potential intensity usually increases fairly quickly to a maximum within two of three decades, decreases and maintains a lower level throughout healthy maturity and then rises as the stand deteriorates or as younger conifers invade the original stand." Although forest age and fire frequency are found to coincide in this study more information is needed before any conclusions can be reached on the role of forest age in this area.

5.2 Weather

Generally, the study area is influenced by a two-component transcontinental moisture gradient, with decreasing air humidity from north to south and increasing air humidity from western Canada to the Atlantic (Barry and Hare, 1974; Heinselman, 1981). This produces complex climatic conditions across the study area. The continental climate has a latitudinal temperature deficit and generally decreasing precipitation patterns. These meteorological patterns generally correspond to the cumulative fire pattern as the number of fires also decreases from south to north and east to west.

The spatial pattern of lightning-caused forest fires relate to weather patterns in that the concentrations of fires in the southwest and along the north shore coincide with mean fire season temperatures of about 14° C or more, rainfall of

90 mm or less and experience approximately 20 days with thunderstorms per fire season. The area in the western region of the province that experiences few fires and the area to the northeast that also has few fires both experience more than 100mm of rain in a fire season. The area to the south of Québec City also has more than 100mm of rainfall and also experiences few fires.

The correlation between major fire years and increased temperature and decreased precipitation are good but not exact. The year with the greatest number of fires 1983 (485) is warmer than previous years but the temperatures of the late eighties are higher. This is of course when the three other extreme fire years occur. Periods of decreased precipitation and high fire years matched well with the exception of Chibougamau in 1983 and La Grande Rivière in 1991.

Both of the low number fire areas to the north of the province experience few thunderstorms. The northeast has a study total of approximately 100 days with thunderstorms for the duration of the study and the west a study total of about 200 to 250 stormy days. The southwest has a low average rainfall and a very high total for thunderstorms, approximately 350 stormy days recorded during the fifteen study years.

Generally, this thesis finds that years with a large number of natural forest fires, > 400 fires, are associated with years which have:

1) increased temperature, less than 1 °C on average;

2) decreased rainfall; while

3) the number of days with thunderstorms remains similar throughout the record.

The results as to the increases for temperature and precipitation were not unexpected. In 1990, Overpeck *et al.* using climate models found that increased temperature led to increased forest disturbance and increased fire. Clark, 1990, found that in relation to changes in climate conditions, fire regimes may be more sensitive than some other forest processes, because fire is responsive to fuel moisture, which depends on precipitation and humidity. High temperatures directly effect lightning-caused forest fires by increasing the fuel drying rate by raising the vapour pressure in the fuel moisture (Chandler *et al*, 1983).

Small magnitude climate changes have resulted in significant alterations in fire patterns (Clarke, 1990). These fire regimes have been found sensitive to mean climate change over decades to centuries, as well as interannual variability of water balance. The weather changes from the beginning of the study period to the end then could be sufficient to explain the fire pattern changes seen in the last five years of the study.

Temperature patterns for the five sample stations show variations of as much as .99 °C and as little as .25 °C for the two time periods (first ten years verses last five and four highest fire years verses the four lowest fire years). In both comparisons the average fire season temperatures are usually higher in the later years and in the years which experience the greater number of fires, albeit in some cases the temperature difference is quite small.

There is only one exception in the precipitation record to the trend of precipitation deficit in either the last five years of the study or high/low fire years. This exception is Val d'Or for the last five years in which the station records an increase of 2.77, Maniwaki had a deficit for the years with few fires of 22.09 mm of precipitation.

There is a correspondence in the decrease in precipitation and an increase in lightning-caused forest fires but the difference is not great. The differences in rainfall range from -22.09 mm to 2.77 mm, although the variation in the average for the rainfall from the high/low fire year sample was a mere 2mm and for the ten/five sample an average difference of 2.92 mm.

When the fire season averages for the meteorological data obtained from the sample stations are reviewed the differences do not appear to be sufficient to explain the increases in the number of fires from the low of 60, (1984) to the high of 485 (1983). It is possible that the time scale used in the study is not sufficiently fine enough to detect the changes effecting the occurrence of lightning-caused forest fires. The fact that the fire frequency high and low records occur in sequential fire seasons points to changes in the necessary conditions for lightning-caused forest fires that occur quickly, certainly within the fires season. There are several studies that point to the periodicity of precipitation and high temperatures at the daily level as more important in creating a fire favourable environment than overall totals.

In a study that focused on wildfire occurrence in the boreal forest of northwestern Ontario, Stocks and Street (1982), found that one or two weeks of dry weather were all that was needed to lay way for "catastrophic wildfire behaviour". The 1982 study found well drained sites needed only an interruption in the regular precipitation to cause rapid drying of the organic fuel and resulting escalation in forest fire risk. The study found that a short period of dry weather, especially in the spring is all that is needed and a longer duration in the dry spell only influences how much of the lowland will burn. Flannigan and Harrington (1988) in another related study on the predictors of the size of an area burned by wildfire found sequences of dry days (0-5mm) to be the important variable. The greater the number of dry days the greater the area burned.

This means that the rainfall in 1983 (485 fires) may have occurred in bursts with long dry-spells in between. 1984 (60 fires) probably experienced showers more frequently with smaller amounts of rainfall in each storm. Here changes in the periodicity of the precipitation distribution is the critical factor and not the total for precipitation.

Thunderstorm data provides a paradox to the study, in that lightning the ignition agent is usually associated with rainfall. Lightning is associated with frontal weather which is usually cloudy, cool, and can be rainy (Flannigan and Harrington; 1988). Fronts can therefore either promote or deter fire activity.

Flannigan and Harrington (1988) point out that lengthy periods of weather, albeit wet or dry, are associated with stationary flow patterns of the westerlies. Severe fire weather is known to be associated with stationary high pressure areas, particularly those associated with blocking (Stocks and Street; 1983). Higher temperatures are also associated with stationary or slow moving high pressure ridges (Flannigan and Harrington; 1988).

These blocking weather patterns can also be used to explain the diverging thunderstorm patterns found in the record. The northern weather stations

Chibougamau, Baie-Comeau and La Grand Rivière showed an increase in the number of stormy days and the southerly stations, Maniwaki and Val d'Or, a decrease in the major fire years. The stationary highs while creating meteorological conditions ripe for fire outbreak, by diverting precipitation to the north and south, also divert the associated storms.

The records for thunderstorm activity indicate decreasing storm activity with increasing latitude which supports the findings of other studies such as Foster, 1982 and Van Wagner, 1982. This however, does not specifically address the regional variation.

Komarek, 1966, in a study of lightning behaviour found that a single storm may provide the ignition source for numerous fires across a very large area. Therefore the development and movement of an individual storm across a region of during a period of fire favourable weather will largely control the distribution pattern of lightning-caused fires.

Finally, in a related study of the relation of meteorological variables to monthly area burned by wildfire in Canada conducted by M. D. Flannigan and J.B. Harrington (1988) it was found that using weather variables as predictors explained only 11% of the variance for the area east of Lake Nipigon. This would indicate that the meteorological variables are probably highly dependent on the other study variables.

Chapter Six

Conclusion

The broad scope of this paper provides documentation of important spatial and temporal patterns in lightning-caused fire occurrence during the period 1978 - 1992. The review of recent fire history is an important step in documenting and interpreting the development and ultimate fate of forest ecosystems facing critical climate conditions (Payette *et al.* 1989). In this paper, annual and monthly fire frequencies are related to fire location, simple meteorological and species variables. The purpose was to determine the extent to which the variation of lightning-caused forest fires could be explained by these variables, and to develop insights into the causes of severe fire months.

Fire activity and meteorological variables showed consistent, albethey minor, differences when related to high and low fire frequency. The meteorological data related to the frequency of fires in that mean fire season temperatures were higher, precipitation was reduced and thunderstorms increased in the north and decreased in the south, in the years with a high number of storms (> 400).

There are two probable explanations for these results, either small meteorological changes create very large changes in the number of lightning-caused forest fires or the variations that are important in creating a fire favourable environment are occurring at a different temporal scale than the one used in the study and are therefore undetectable.

Sufficient variability is exhibited in the temperature, precipitation and days with thunderstorms, however, to emphasize the complex and often stochastic factors that control the coincidence of ignition potential and suitable fuel conditions.

Lightning-caused fires are dependent on the availability of adequate fuel and an ignition source. The study found that the geography of fires is always limited to the spatial confines of an overall pattern, while the number of fires within this geographic outline changes over time. This leads to the conclusion that these two entities, location of fires and number of fires are governed by different parameters. It appears that the number of fires, or more importantly the variables controlling them, is not a determining factor in the location or spatial distribution of lightning-caused fires. This does not preclude temporal, or weather, aspects influencing the spatial component. The vegetational landscape is a result of the interrelationship of the temporal and spatial pattern of fire acting within the physiographic and climate setting of Québec. Weather patterns are a contributor to the success and distribution of any species of plant life.

Forest species and forest age are usually slow to change and were considered as static during the study period. The geography of forest species plays an important role in determining what areas are available for combustion should ignition occur. Forest species and forest age are important factors in delimiting the geographic extent of lightning-caused forest fires.

The weather variables are dynamic, changing on a yearly, monthly and daily basis and as such are considered as temporal entities in constant flux.

Understanding fire outbreak with weather change remains challenging because of the complex relationships among weather and fuel. The process of fire in the forest environment is complicated with intricate facets; however, the basic recipe for fire, fuel, match, oxygen, remains the same.

No matter what the weather, if the fuel is not available the number of fires will be reduced. The areas that have suffered large scale cutting, disease, or the intrusion of agriculture or urban activities will have reduced fires. As infringement by human activity grows the number of lightning-caused fires will drop.

The decrease in fires from south to north coincides with changes in species, mainly from deciduous to coniferous; fluctuations in percent coverage of the forest, decrease in temperature, fluctuations in precipitation and in the number of thunderstorms.

The match, lightning, is introduced in a pattern that varies over the individual fire season and across the record of many seasons. Weather, is an important influence bounding the temporal variation and is crucial in determining if and when a fire will start. The fuel appears to be more important in the spatial question of whether lightning strikes will encounter a suitable combustible fuel. Factors such as the size and chemistry of the fuel play an important role in the ignobility. Moisture content is perhaps the most important factor in ignition and combustion and this is dependent on the weather pattern (Chandler *et al*, 1983).

The more important meteorological factors that will determine susceptibility to fire in the coming years will be changes in the frequency and duration of blocking highs rather than rainfall. These stable high pressure systems steer moisture from the Pacific and the Gulf of Mexico northward across northern Québec and eastward below the Great Lakes respectively. As a result the flow of moist air is effectively blocked for extended periods.

6.1 Recommendations for Future Research

Research into changing climatic conditions is at the forefront of scientific inquiry as we try to explain, predict, and prepare for the twenty-first century. It is proposed that climate will warm at an unprecedented rate because of the increase in the atmospheric content of radiatively active gases such as methane, carbon dioxide, water vapour, methane, nitrous oxide and chloroflurocarbons. Predictions, founded on work with general circulation models (GCM) suggest the increase in global temperature will be in the range of 1.5-5.0 °C (Schlesinger and Mitchell 1987). The increase in temperature is also predicted to rise with increasing latitude (Graham, Turner & Dale 1990).

Once the contributors to forest fire have been established the factors can be refined and used as contributors to a formula for the prediction of natural forest fires and then to relate this to climate change. Few objective research projects on potential future fire regimes have been conducted, although there is a plethora of informal speculations on the topic (Flannigan M. D. and C. E. Van Wagner 1991)

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APPENDIX I

Record Layout for Fire Data Base

DBF f
NAME

DESCRIPTION DE L'ECRAN DE SAISIE :

	CHAMP	DESCRIPTION	VALEURS ACCEPTEES
(FIRE_N)	FEU	Numéro du feu	Entre 001 et 999. Le programme ajoutera le numéro de la société + "0". ex. feu 1 deviendra 50001 pour la société 5.
(YEAR MONTH DAY)	DATE	Date de début du feu	Du 1er mars à aujourd'hui si l'année est l'année courante, ou du 1er mars au 31 novembre pour les années historiques.
(STATUS)	CD	Condition du feu	Entre 1 et 8
(GRID)	QUADRILLAGE	Point d'origine du feu	S.1 [39-75,11-22]-[1-9]-[00-66,00-93] S.2 [22-41,04-13]-[1-9]-[00-66,00-93] S.3 [20-42,08-22]-[1-9]-[00-66,00-93] S.4 [37-93,17-75]-[1-9]-[00-66,00-93] S.5 [20-41,16-75]-[1-9]-[00-66,00-93] S.6 [06-27,06-18]-[1-9]-[00-66,00-93] S.7 [02-48,10-75]-[1-9]-[00-66,00-93] S.8 [00-99,00-99]-[1-9]-[00-66,00-93]
ECT_PROT)	SC	Section de protection	Entre 1 et 3
CAUSE)	CG	Cause Générale	Entre 1 et 8
(AREA)	SUPERF	Superficie du feu	Entre 0.0 et 99999.9
(COST)	COUT	Dépenses encourues	Entre 0 et 99999999
TYPE_FEU)	T	Type de Feu	Entre 1 et 3
N_GEST)	UG	Unité de Gestion	Entre 00 et 99
URCE_IGN)	SI	Source d'ignition	Selon les Normes et Directives du MER
_RESP)	GR	Groupe Responsable	Selon les Normes et Directives du MER
ETECT)	D	Mode de Détection	Entre 1 et 4, 6 ou 9
_INI)	A	Mode d'attaque initiale	Entre 1 et 8
)	R	Code de remboursement	Entre 0 et 2

	CHAMP	DESCRIPTION	VALEURS ACCEPTEES
(FFMC)	ICL	Indice de combustible léger	Entre 0 et 101
(DMC)	IH	Indice de l'humus	Entre 0 et 100
(DC)	IS	Indice de sécheresse	Entre 0 et 100
(ISI)	IPI	Indice de propagation initiale	Entre 0.0 et 999.9
(BUI)	ICD	Indice du combustible disponible	Entre 0 et 100
(FWI)	IFM	Indice de forêt-météo	Entre 0 et 100
(DSR)	GR	Indice de gravité	Entre 0 et 99
(TIMESTAMP)	ENTREE AU VAX		Champ inaccessible par l'usager

DESCRIPTION EXHAUSTIVE DES CHAMPS :

CONDITION : STATUS

Code numérique décrivant la condition du feu. Un feu actif aura un condition variant entre 1 et 5, un feu éteint aura une condition 6, 7 ou 8. La valeur 7 est acceptée seulement lorsque le feu a été déclaré éteint au préalable (cond 6). Ces codes sont :

1 - Feu nouveau
2 - Feu sous-observation
3 - Feu hors contrôle
4 - Feu contenu
5 - Feu maîtrisé
6 - Feu éteint
7 - Feu éteint révisé
8 - Feu facturé

QUADRILLAGE : GRID

Si un feu vient d'être rapporté , seulement les cinq(5) premiers chiffres sont nécessaires. Le programme s'occupera d'ajouter les zéros. Par contre, s'il s'agit d'un feu révisé éteint (cond 7), le quadrillage doit se composer de neuf(9) chiffres. Un message vous indiquera de vérifier le quadrillage lorsque vous assignerez une condition 7 à un feu.

SECTION DE PROTECTION : SECT. PROT

Code numérique correspondant à la section de protection du territoire où le feu a pris naissance. Ces codes sont :

1-Intensive 2-Restreinte 3-Hors Territorial

Les valeurs permises pour une société sont :

Société 1 - 1 ou 3
Société 2, 3, 6 - 1
Société 4, 5, 7 - 1, 2 ou 3

CAUSE GENERALE : CAUSE

Code numérique correspondant à la cause générale de l'incendie. Ces codes sont :

1 - Foudre
2 - Chemin de fer
3 - Opérations forestières
4 - Opérations industrielles
5 - Incendiaires
6 - Résidants
7 - Récréation
8 - Diverses

SUPERFICIE : AREA

Superficie incendiée en terrain forestier évaluée au dixième d'hectare.

COUT :
Dépenses encourues jusqu'à aujourd'hui dans les opérations relatives à l'extinction du feu. Le coût est estimé en dollar et est arrondit au $ près.

TYPE DE FEU :
Code numérique décrivant le type de feu. Trois(3) valeurs sont permises soit :

1 - Feu de forêt
2 - Feu de champ
3 - Autres

UNITE DE GESTION :
Numéro de l'unité de gestion où le feu a pris naissance. Les valeurs permises correspondent à une des unités de gestion incluse à l'intérieur des limites de la société. Les valeurs acceptées pour une société sont :

Société 1 : 11, 12, 13, 14, 15, 35
Société 2 : 34, 35, 41, 51, 62
Société 3 : 21, 22, 25, 26, 31, 32, 33, 41, 42, 43, 61, 62
Société 4 : 23, 91, 92, 93, 94, 95, 96
Société 5 : 21, 22, 23, 24, 25, 26, 27, 42, 91, 92, 93
Société 6 : 43, 61, 62, 63, 64, 71, 72, 73, 74, 81, 83, 84
Société 7 : 00, 26, 42, 43, 74, 81, 82, 83, 84, 85, 86, 87

SOURCE D'IGNITION :
Code numérique correspondant à la source d'ignition du feu. Ce code entré est établi et validé selon LES NORMES ET DIRECTIVES du MER. Si la source d'ignition est "Brûlage dirigé", les champs suivants devront être complétés comme suit :

Cause : 3
Groupe Responsable : 32
Source d'ignition : 46
Code de Remboursement : 2

Si la cause est "Foudre", les champs optionnels suivants devront être complétés comme suit :

Cause : 1
Groupe Responsable : 10
Source d'ignition : 10
Code de Remboursement : 0

GROUPE RESPONSABLE : GR_RESP

Code numérique correspondant au groupe responsable du déclenchement de l'incendie et qui est établi selon LES NORMES ET DIRECTIVES du MER. La valeur permise est composée de deux chiffres dont le premier chiffre correspond toujours à la valeur entrée au champ CAUSE. Si la cause générale est "Foudre", les champs optionnels devront être complétés comme suit :

Cause : 1
Groupe Responsable : 10
Source d'ignition : 10
Code de Remboursement : 0

MODE DE DETECTION : DETECT

Code numérique correspondant à l'agent qui a découvert l'incendie. Ces codes sont :

1 - Avion de détection
2 - Personnel de Conservation
3 - Autre aéronef
4 - Ouvrier forestier
6 - Garde-feu municipal
9 - Autre

MODE D'ATTAQUE INITIALE : ATT_INI

Code numérique correspondant au groupe d'attaque initial. Ces codes sont:

1 - Equipe de choc ou EMC
2 - Ouvriers forestiers
3 - Employer de chemin de fer
4 - Garde-feu
5 - Employé municipal
6 - Avion-citerne
7 - Autre
8 - Incendie non combattu

CODE DE REMBOURSEMENT : REMB

Code numérique indiquant le mode de paiement des frais d'extinction d'un incendie. Ces codes sont :

0 - Feu payable 50/50 (section de protection intensive ou restreinte)
1 - feu payable à 100% par un tiers
2 - feu payable en vertu de la directive sur le brûlage dirigé à des fins sylvicoles.

Si le code de remboursement entré est "2", les champs optionnels suivants devront être complétés comme suit :

Cause : 1
Groupe Responsable : 10
Source d'ignition : 10
Code de Remboursement : 0

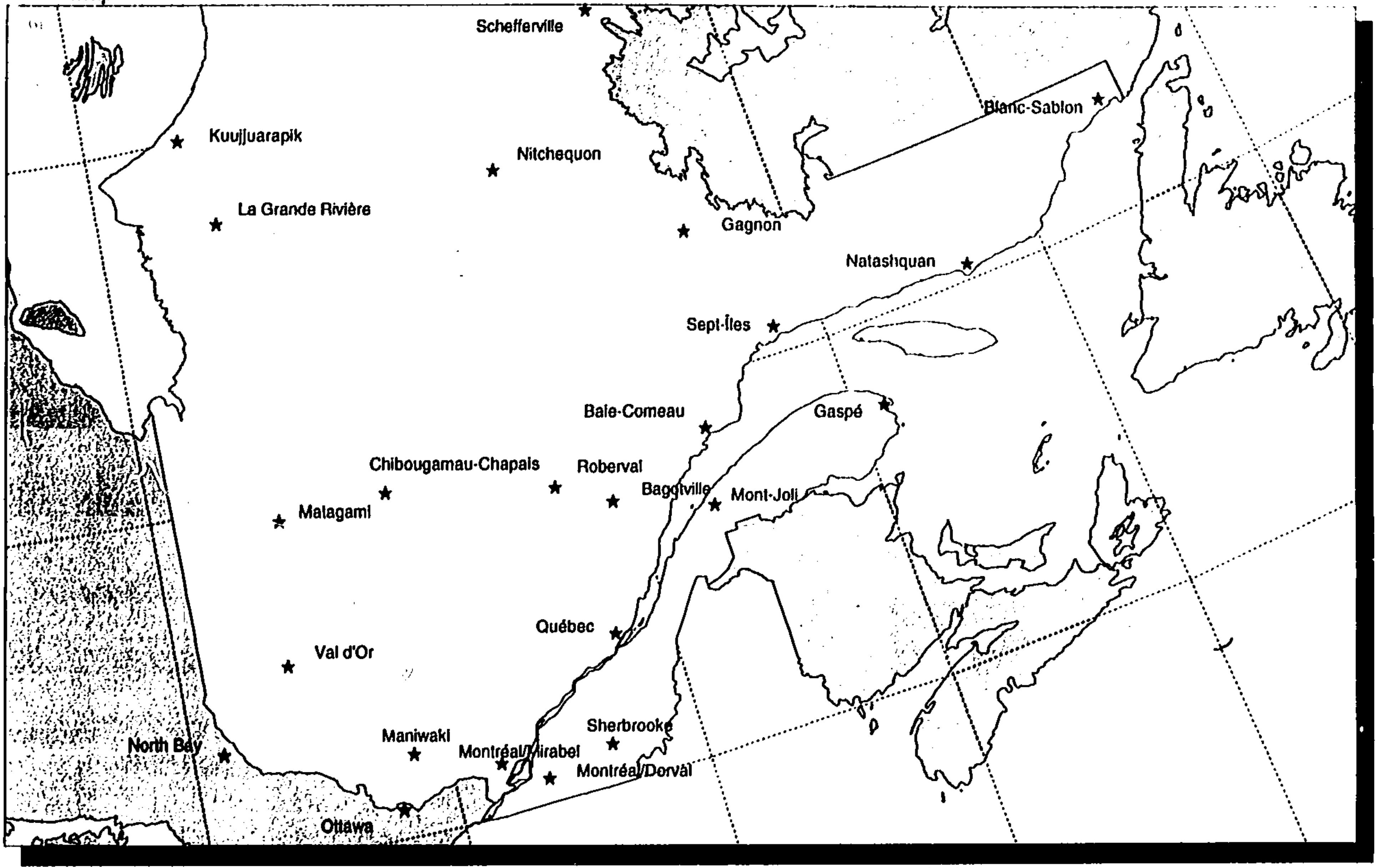
ENTREE AU VAX timestamp

Cette entrée au VAX vous permet de connaître la date et l'heure de la dernière modification effectuée pour ce feu. La date se lit selon le format AAMMJJ. Si cette entrée au VAX est uniquement constituée de zéros (000000 00:00), ceci indique que les données de ce feu n'ont pas été envoyées dans le réseau via l'option "MISE-A-JOUR".

APPENDIX II

Environment Canada Weather Stations

Map 15. Environment Canada Weather Stations



Environment Canada Weather Stations

Schefferville A

Quaqtaq

Val d'Or A

Nitchequon

Matagami A

Roberval A

Sept-Îles A

Natashquan A

North Bay A

Ottawa Int'l A

Québec A

Montréal/Dorval Int'l A

St-Hubert A

Sherbrooke A

Montréal/Mirabel Int'l A

Maniwaki

Baie-Comeau A

Blanc-Sablon A

Gaspé A

Mont-Joli A

Bagotville A

Chibougamau-Chapais A

La Grande Rivière A

Inukjuak

Kuujjuarapik A

Kuujjuaq A

Gagnon A. (data for thunderstorms not available)

APPENDIX III

Tables

Table 5. Mean Summer Temperature, April - September, for Selected Stations, 1978-1992

	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92
Man	14.7	14.8	14.4	14.8	14.5	15.4	14.4	14.7	14.1	15.3	15.6	15.8	15.1	15.6	14.2
Vald	13.1	13.8	12.7	13.4	13.2	13.9	12.8	12.8	12.3	13.9	14	14.1	13.2	14.1	12.4
BalC	11.6	12.2	11.7	11.9	10.9	12	16.5	11.7	10.9	11.6	11.8	12.3	12	12.1	11.3
Chlb	11.6	11.8	11.7	12.6	11.9	12.2	12	11.2	10.9	12.3	12.2	12.8	11.7	12.1	11.3
LaG R	8.4	9.5	9.3	9.8	9.2	9.9	8.8	9.5	8.9	9.6	10.2	9.8	9.1	10.3	8.3

Table 6. Mean Summer Precipitation, April - September, for Selected Stations, 1978 - 1979

	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92
Man	76.9	94.6	109.5	94	59.9	77.8	88.8	74.2	122	83.7	89	91.5	82.9	62.6	99.4
Vald	76.1	116.9	90.5	74.3	80.1	74.6	103.5	103.2	100	86.3	99.9	89.3	107.9	75.4	94.1
BalC	53	96.3	117.9	106.1	85.1	83.9	84.7	81.8	97.9	75.8	85.7	65.9	83.8	63.3	106.2
Chib	126.3	124.4	108.6	87.1	92.6	117.8	89.1	89.8	106.7	111.9	104.2	87.8	123	98	m
LaGR	80.5	m	77.4	83.4	m	85.7	75.5	59.8	82	93.2	73	52.2	69.8	91.1	91.2

m = missing records

Table 7. Number of Days with Thunderstorms, April - September, for Selected Stations

1978 - 1979

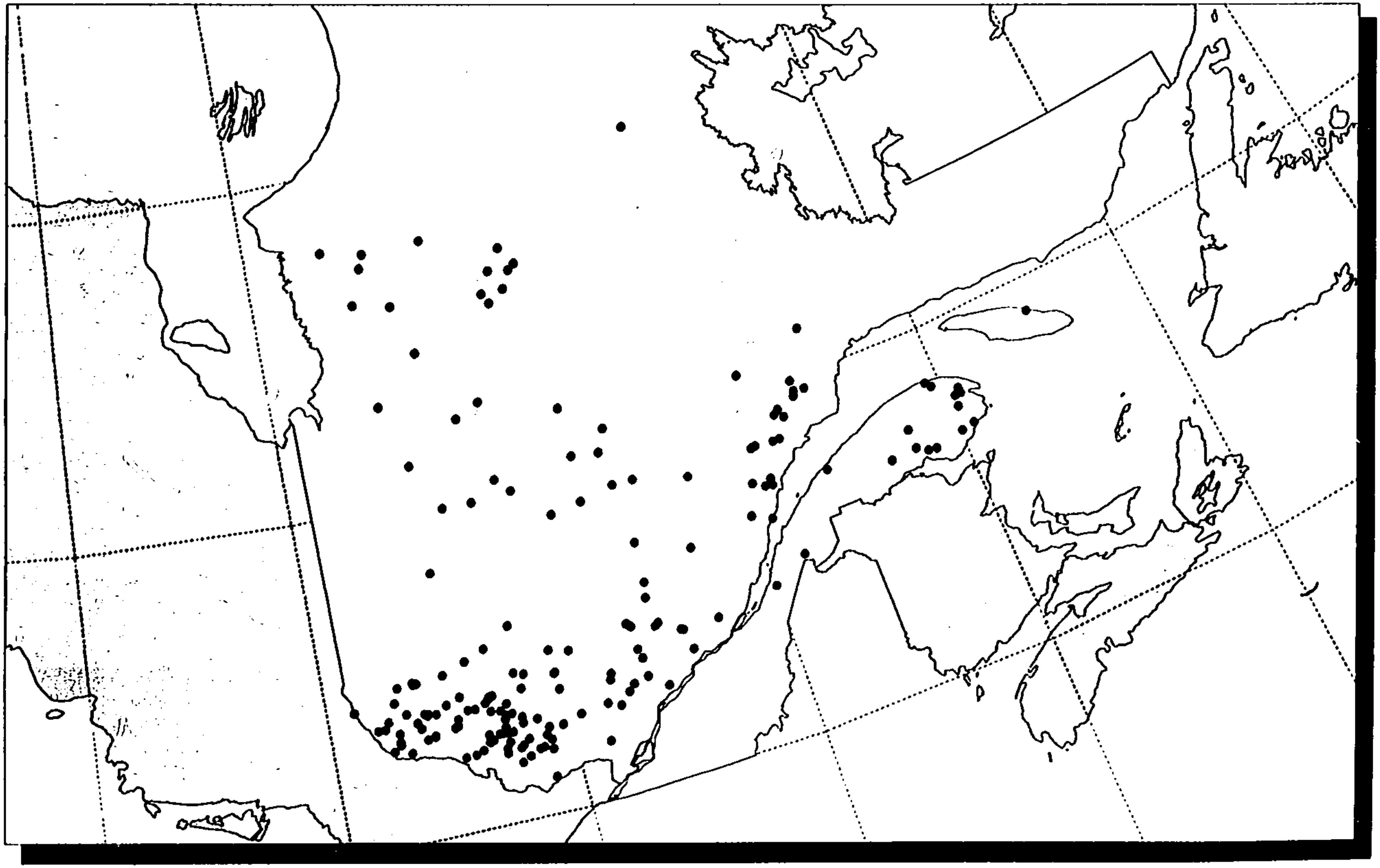
	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92
Man	22	16	16	23	14	26	27	23	19	27	28	16	22	20	14
Vald	21	26	14	15	20	16	22	22	22	27	23	24	14	20	15
BalO	8	17	14	10	7	16	10	9	8	15	8	14	10	13	14
Chib	27	26	19	19	13	26	23	17	17	25	23	24	16	22	m
LaGR	6	m	9	8	9	15	12	4	4	10	3	10	6	17	9

m=missing record

APPENDIX IV

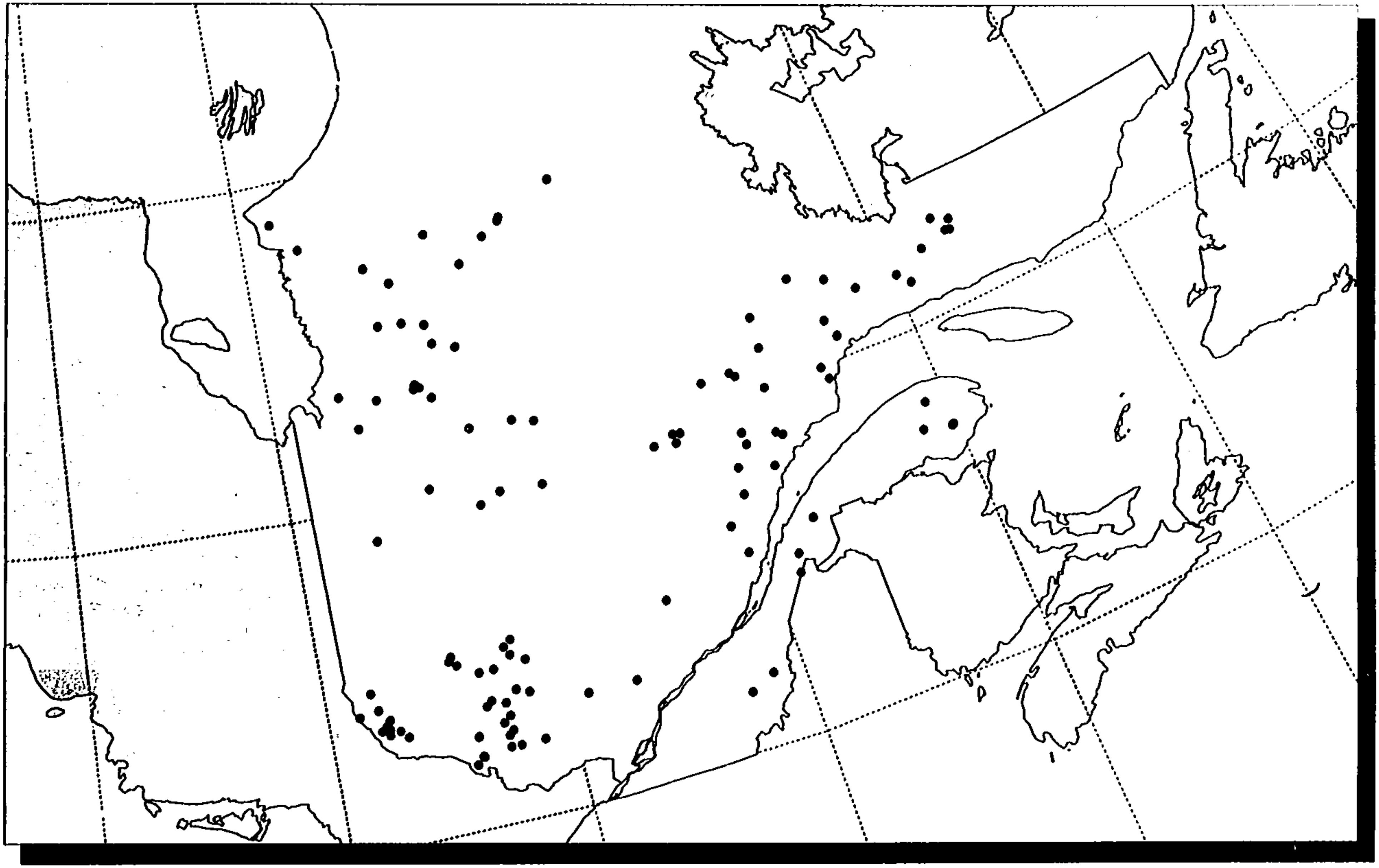
ANNUAL FOREST FIRE MAPS

Lightning Fires, 1978



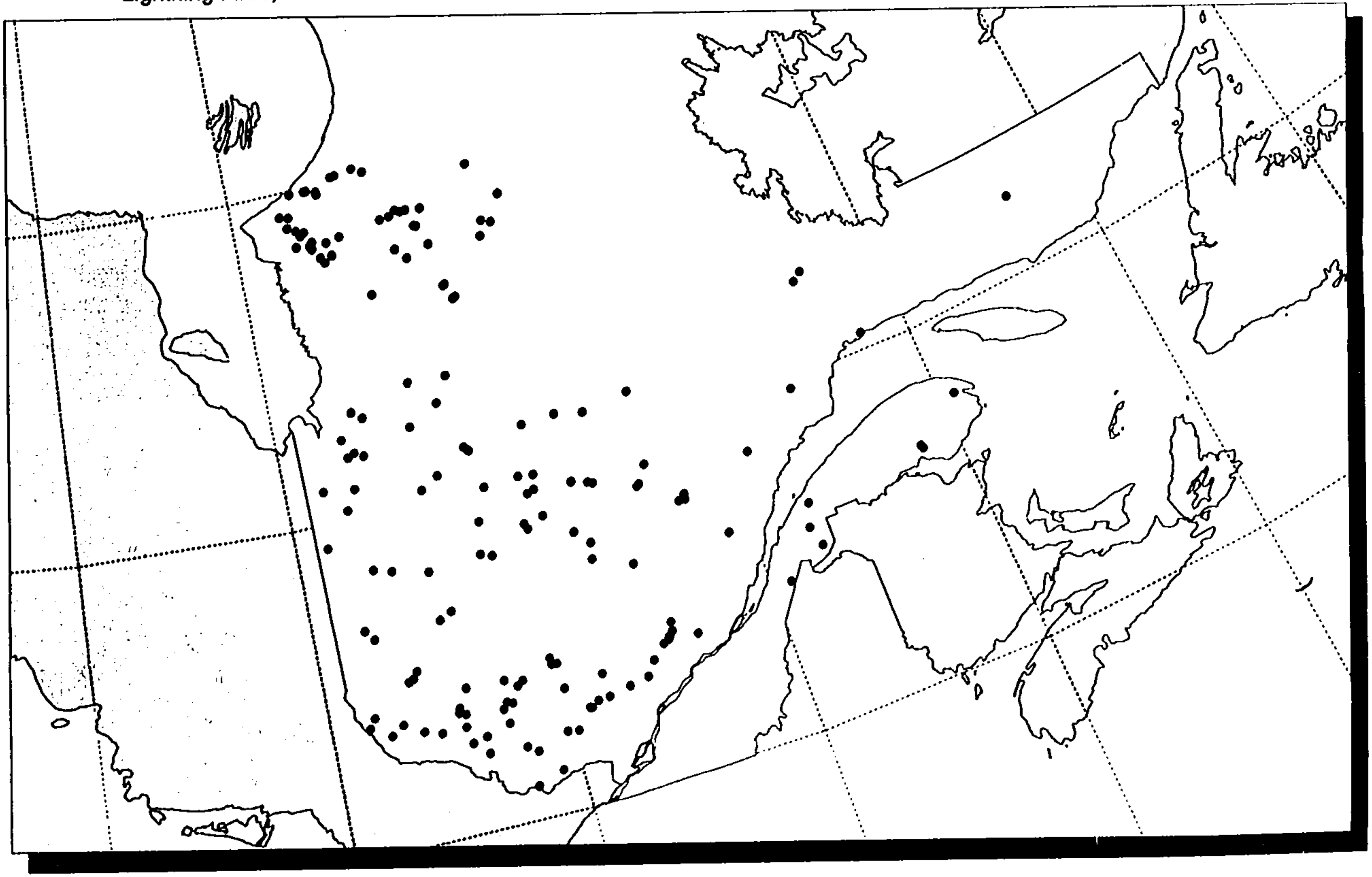
scale 5 cm = 448 km

Lightning Fires, 1979



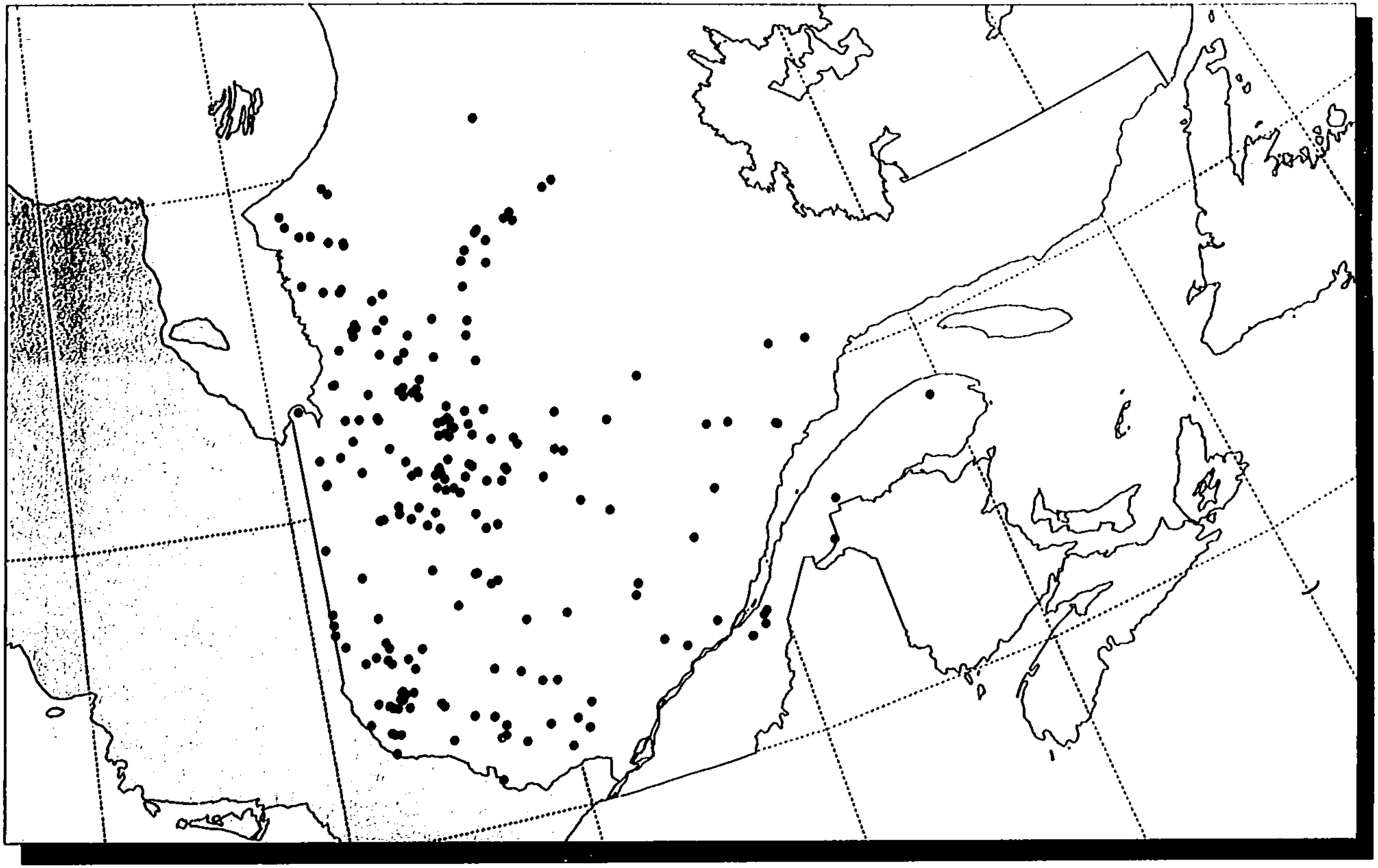
scale 5 cm = 448 km

Lightning Fires, 1980



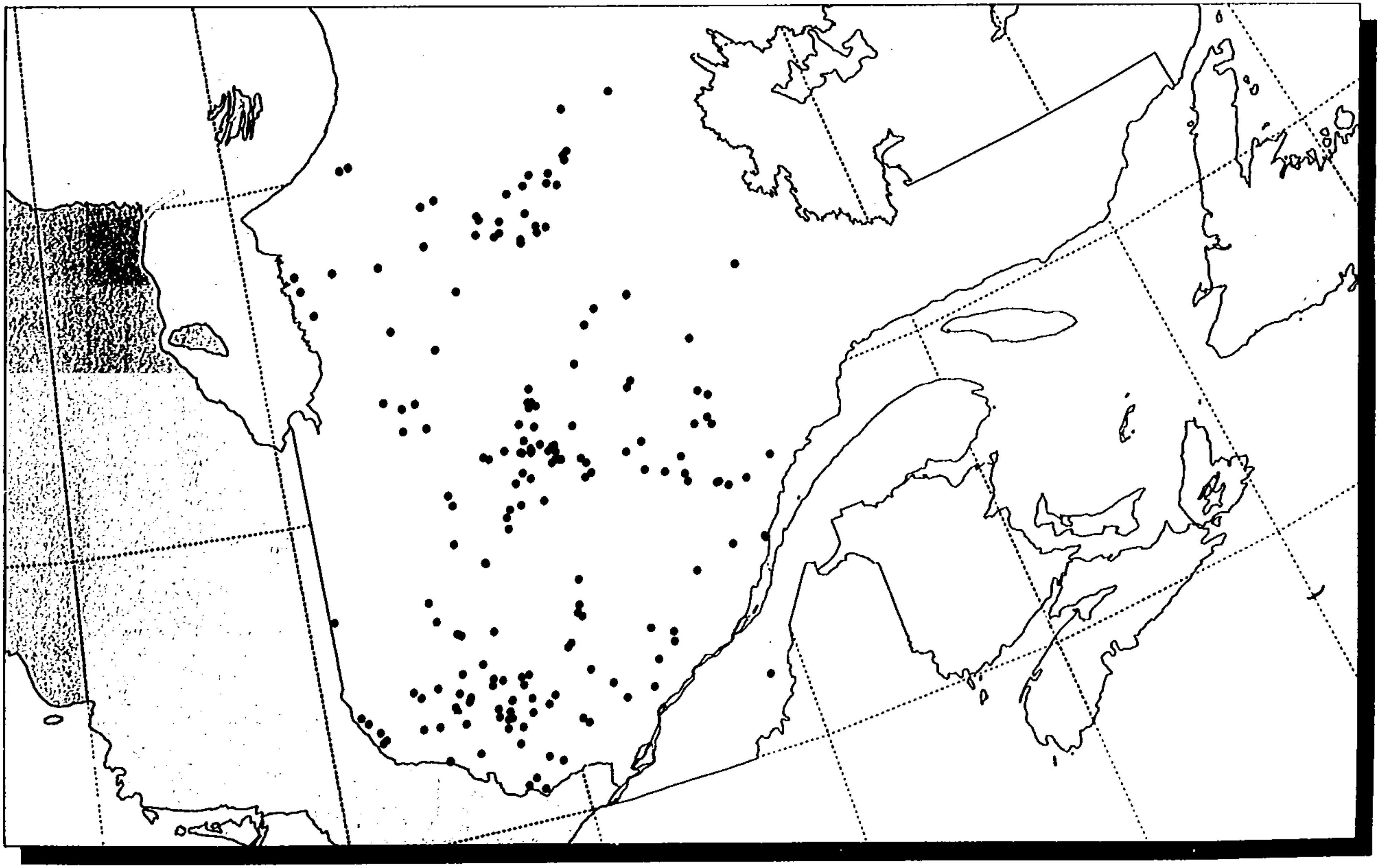
scale 5 cm = 448 km

Lightning Fires, 1981



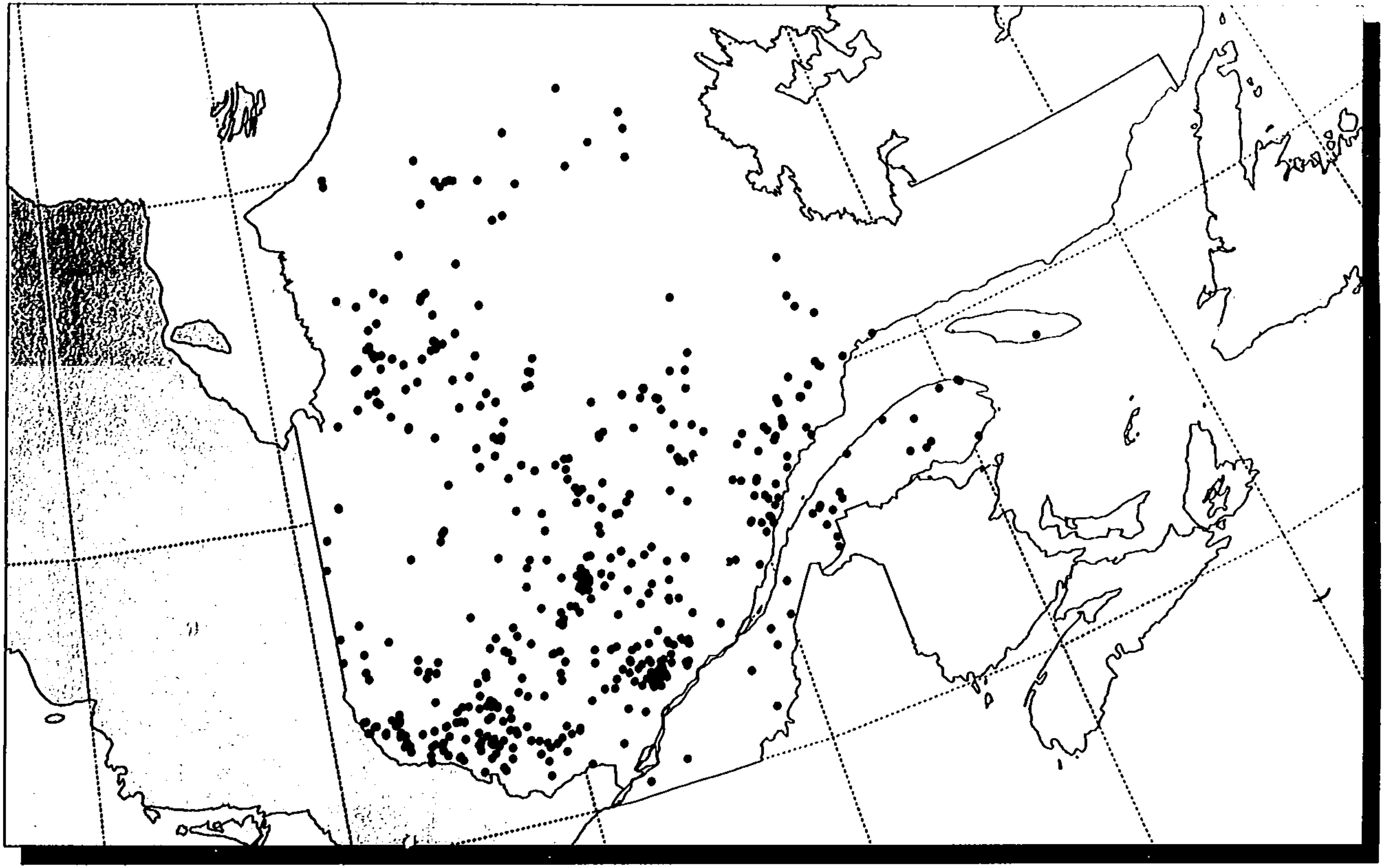
scale 5 cm = 448 km

Lightning Fires, 1982



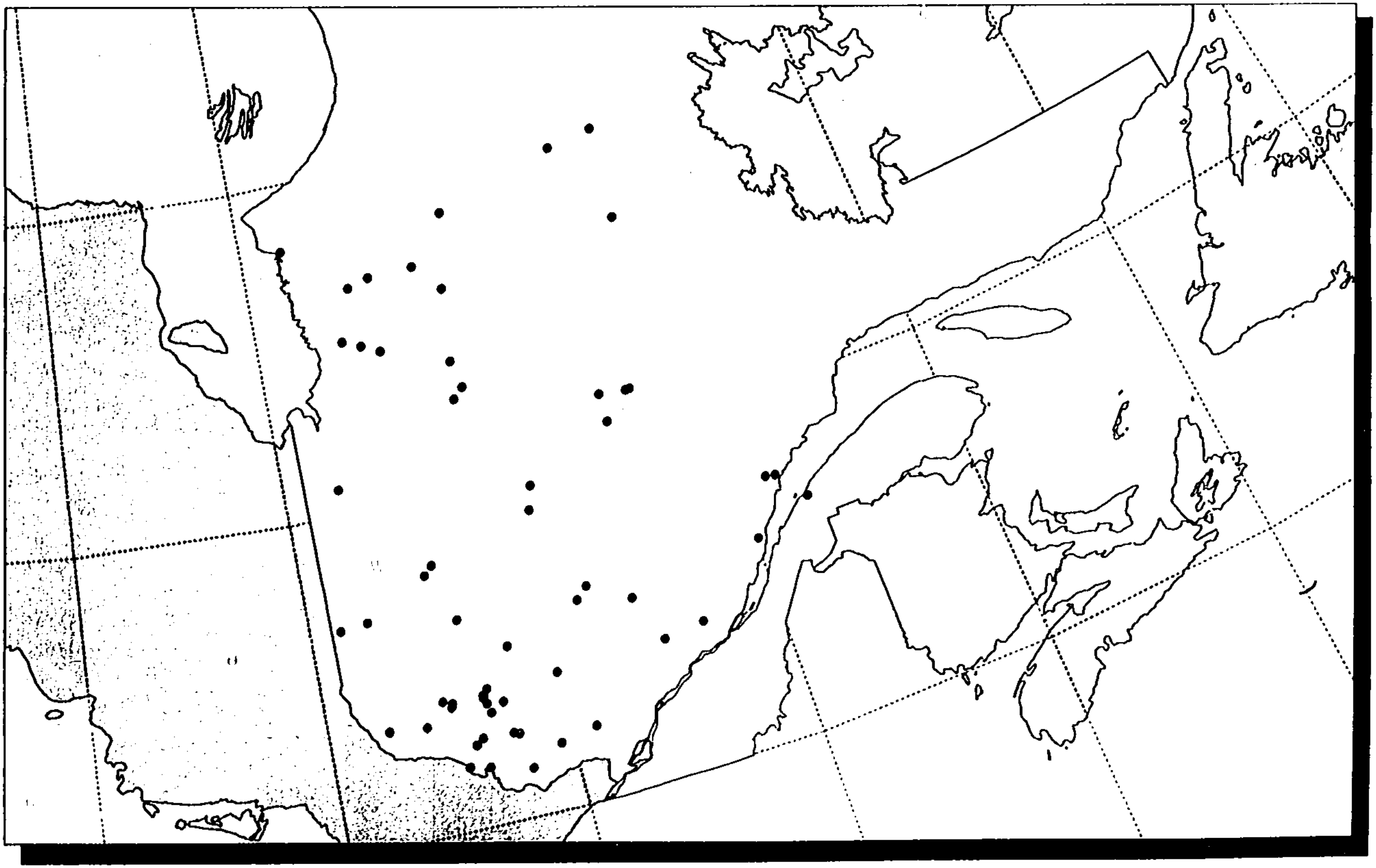
scale 5 cm = 448 km

Lightning Fires, 1983



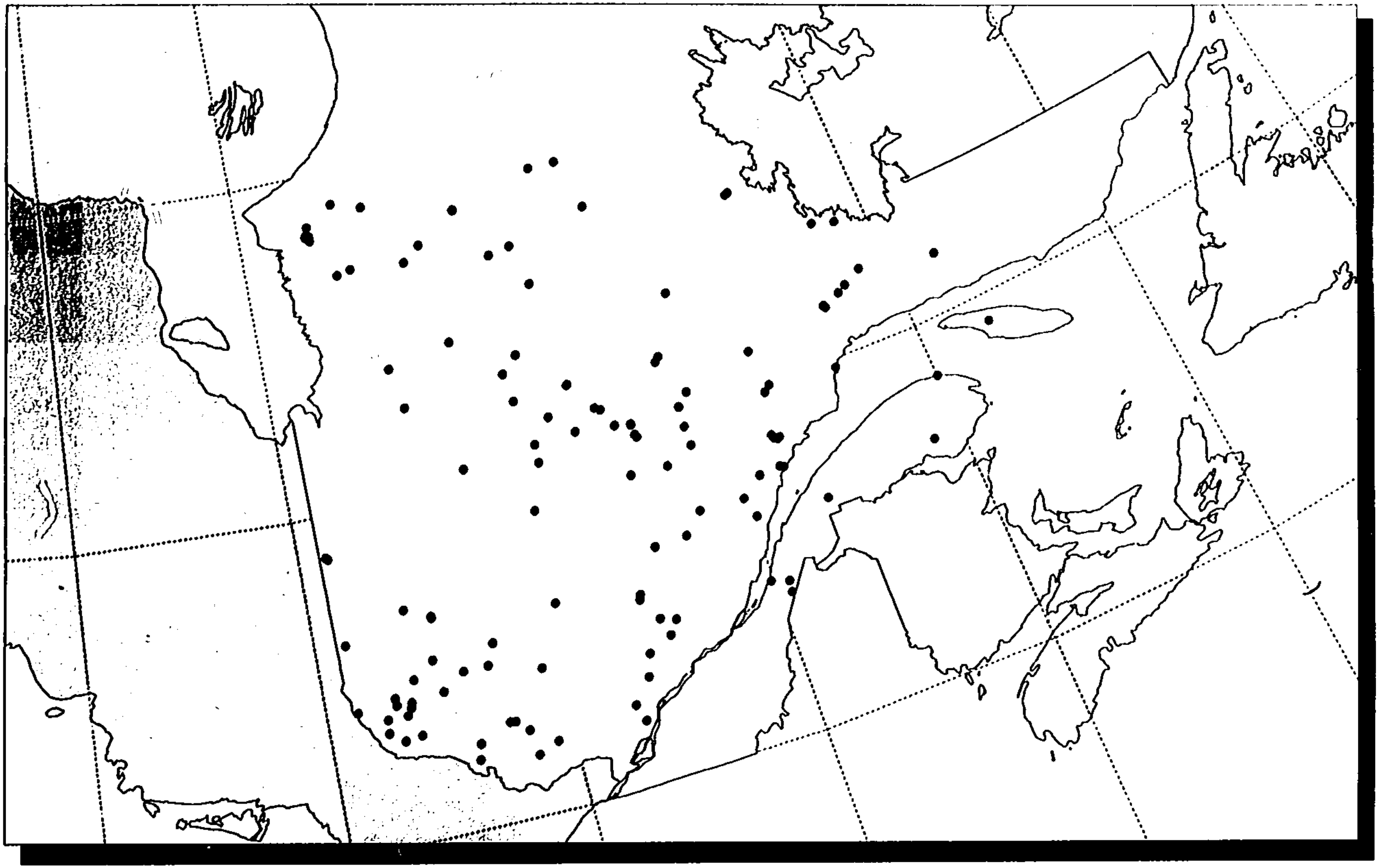
scale 5 cm = 448 km

Lightning Fires, 1984



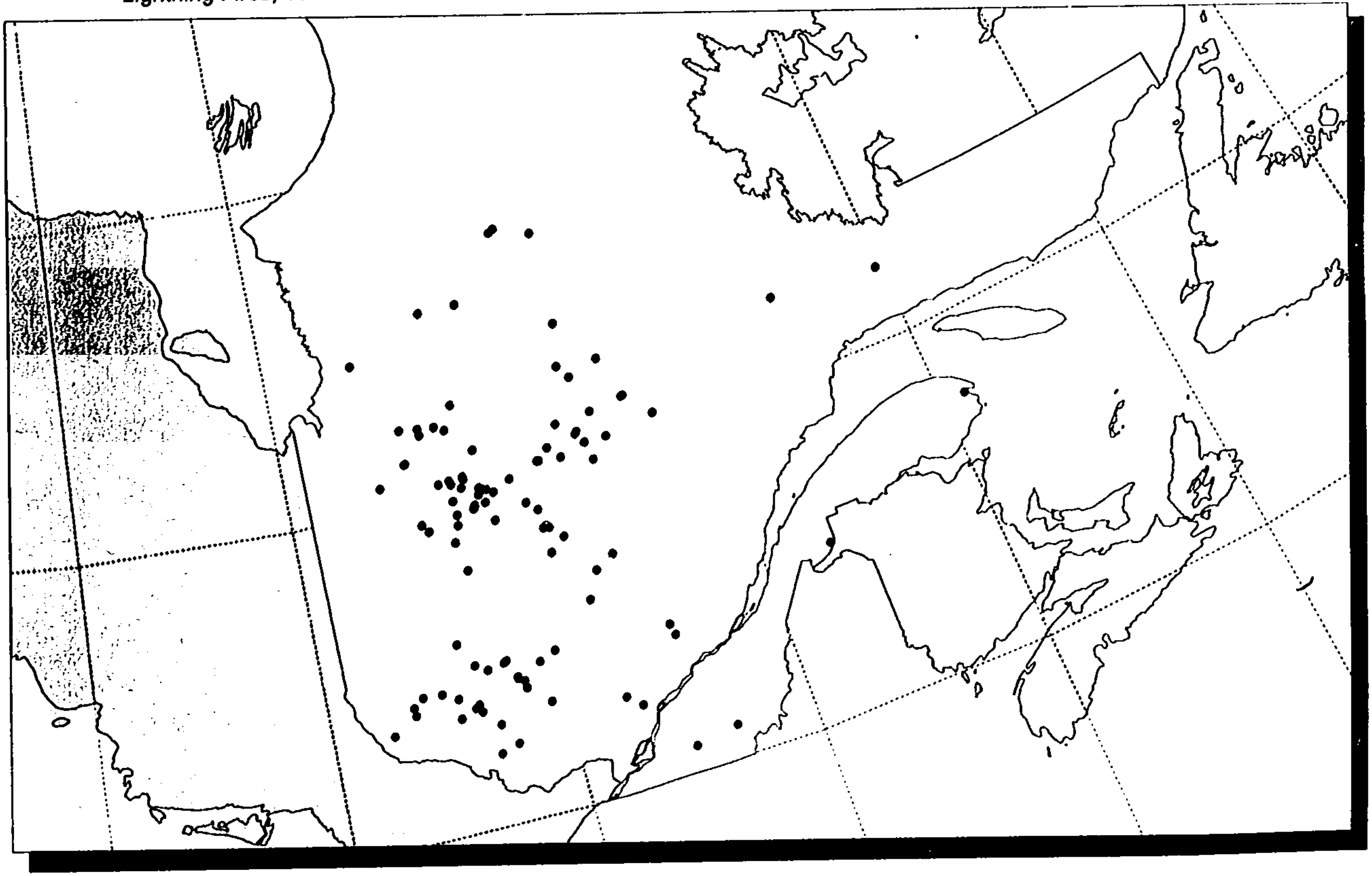
scale 5 cm = 448 km

Lightning Fires, 1985



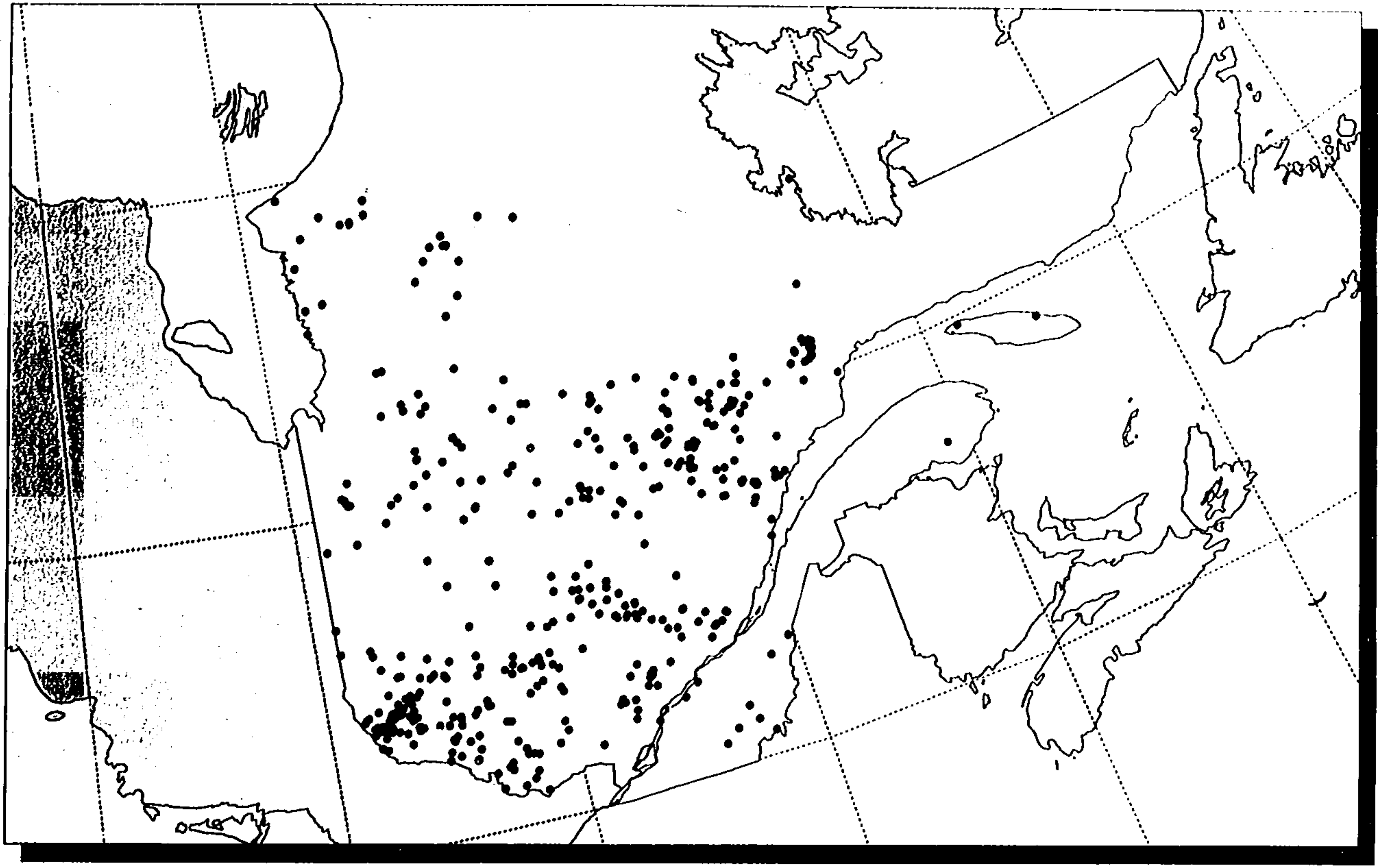
scale 5 cm = 448 km

Lightning Fires, 1986



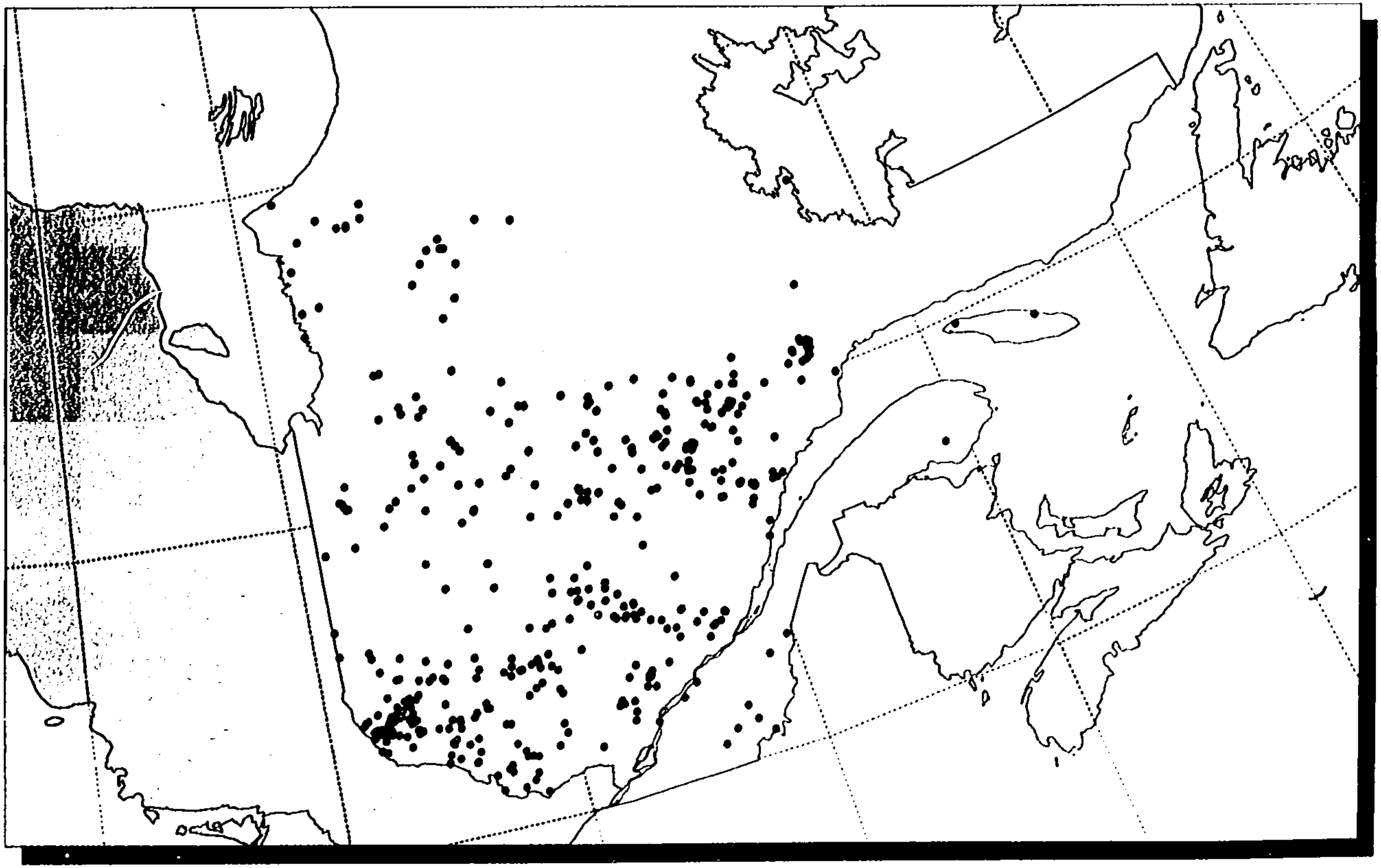
scale 5 cm = 448 km

Lightning Fires, 1987



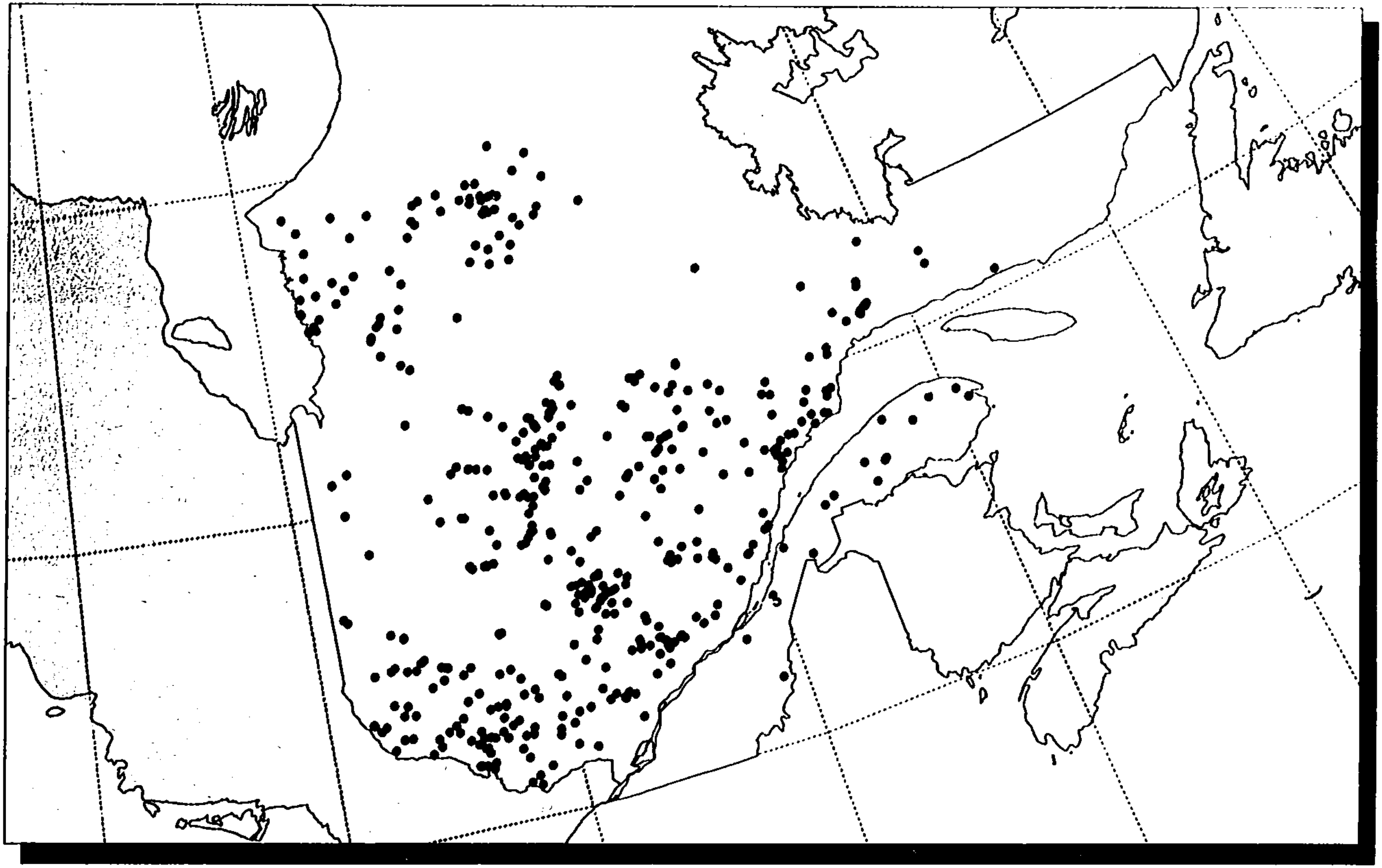
scale 5 cm = 448 km

Lightning Fires, 1988



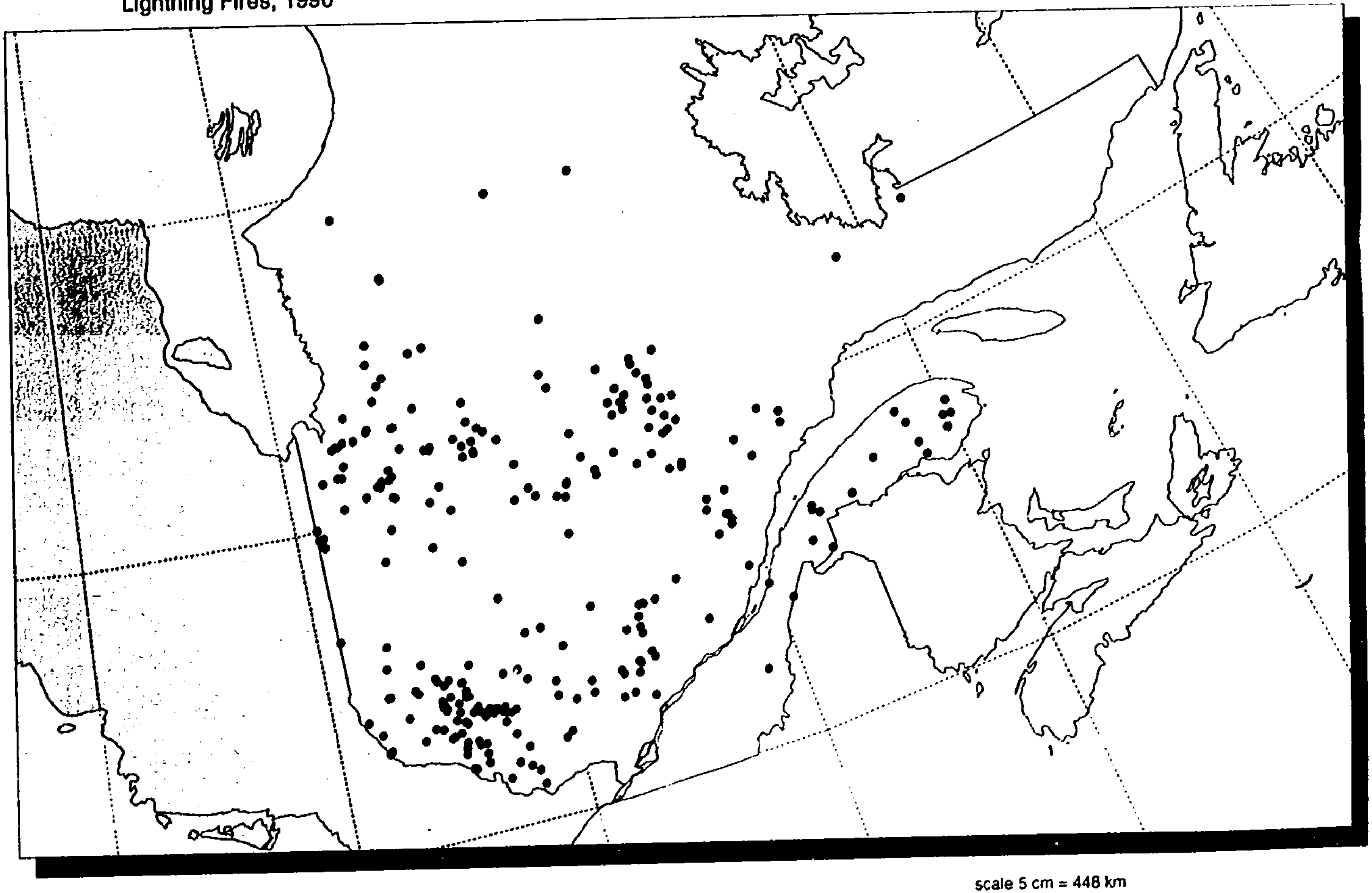
scale 5 cm = 448 km

Lightning Fires, 1989



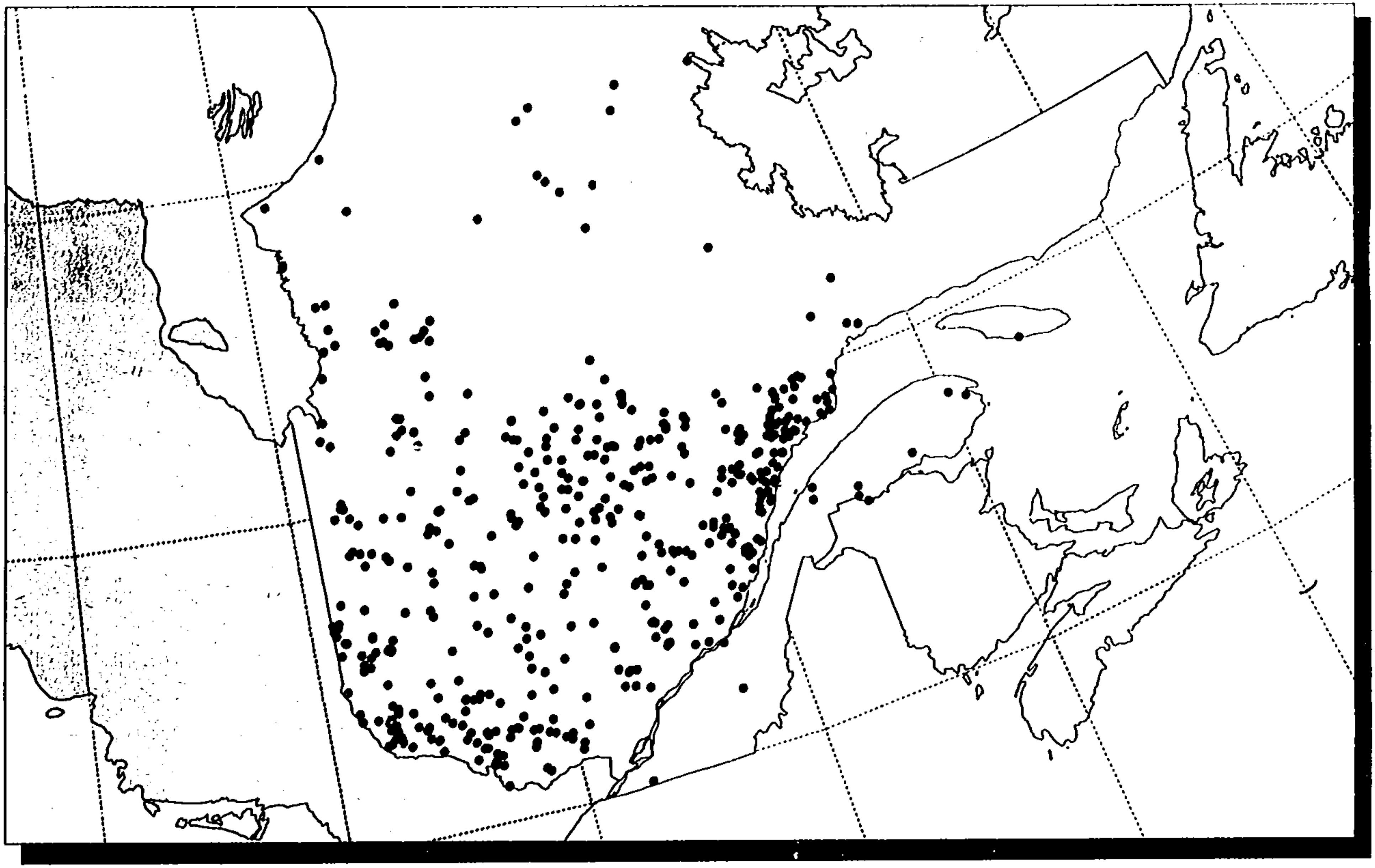
scale 5 cm = 448 km

Lightning Fires, 1990



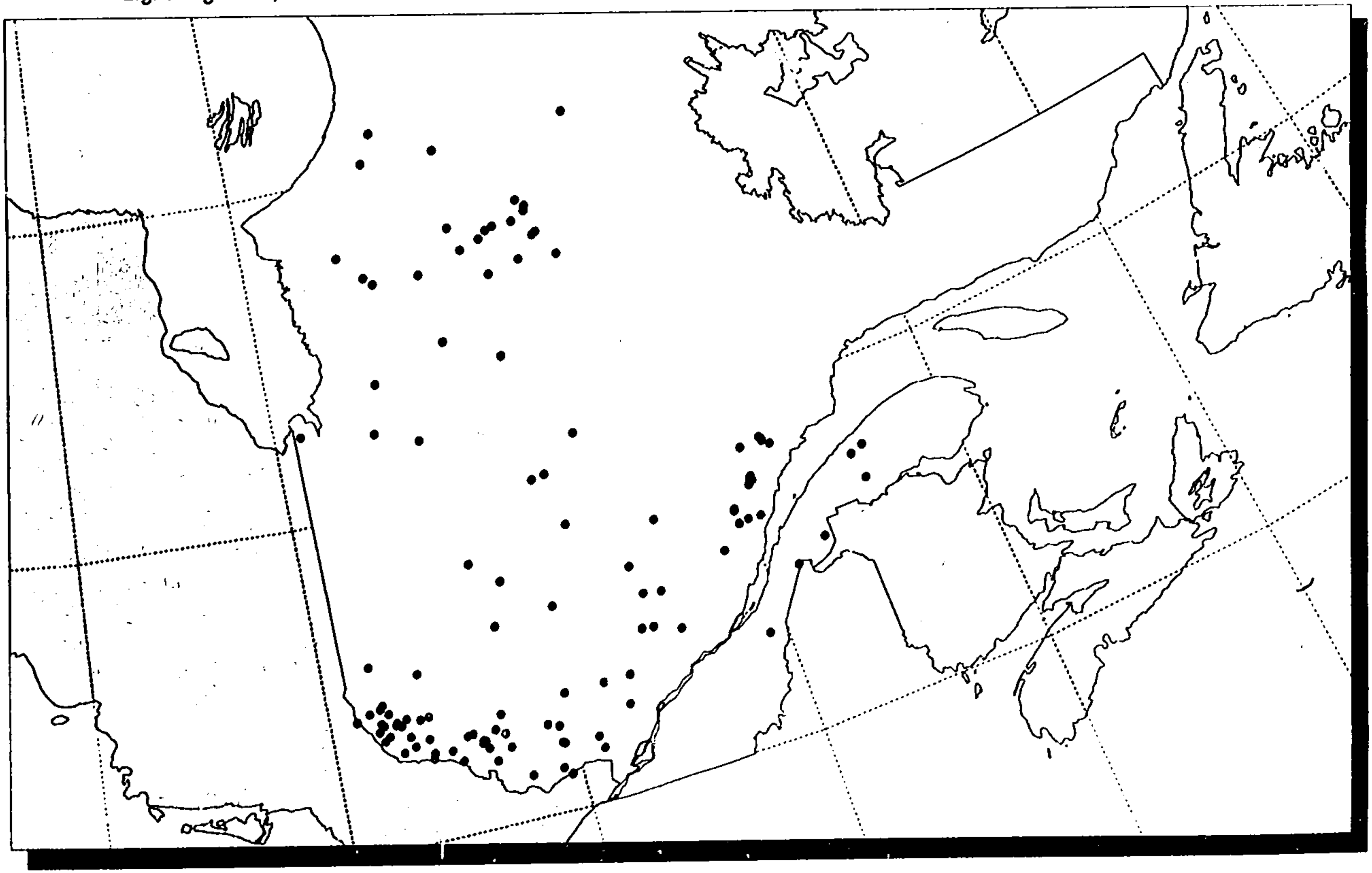
scale 5 cm = 448 km

Lightning Fires, 1991



scale 5 cm = 448 km

Lightning Fires, 1992



scale 5 cm = 448 km