A LIGHTNING CLIMATOLOGY FOR MANITOBA USING CLOUD-TO-GROUND STRIKE DATA FROM A LIGHTNING DETECTION NETWORK

by

Irene Hanuta

A thesis presented to the University of Manitoba
in partial fulfillment of the requirements
for the Master of Arts degree in

The Department of Geography
The University of Manitoba

Winnipeg, Manitoba, Canada
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A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

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ABSTRACT

While thunderstorm data have been traditionally collected at first order weather stations, this thesis uses lightning detector data with a higher spatial and temporal resolution as a source of thunderstorm information. Cloud-to-ground lightning strike data for Manitoba during 1985 have been analyzed for spatial variability and diurnal/seasonal distribution. Almost 68 000 strikes were detected over a four month period with July recording the most activity. Three areas of the province had the greatest concentration of lightning strikes, indicating some influence by topography and position of large lakes. Comparisons are made between thunderstorm climatologies derived from lightning detectors and those from weather stations. Forest fire and Manitoba Hydro disruption data are compared with lightning distributions. A selection of the most active lightning storms was chosen in order to study associated weather patterns.

ACKNOWLEDGEMENTS

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I am very happy to dedicate this thesis to my dad, Nick Hanuta.

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CHAPTER 1
INTRODUCTION

1.1 OBJECTIVES

The objectives of this study include a preliminary presentation of a lightning climatology for Manitoba showing frequency distributions of all lightning strikes in time and space and their variability. Areas will be identified which experience high lightning frequencies. Times when lightning is more common will also be identified for different parts of the province. Recently available information from a lightning detection network will be compared with traditional Atmospheric Environment Service (AES) thunderstorm data to provide an improved thunderstorm climatology for Manitoba. Comparisons will be made between lightning detector data and forest fire occurrences and power disruption locations. A synoptic weather analysis of typical lightning storms will also be presented. Using lightning detector data in conjunction with other weather data to examine synoptic patterns and lightning distributions can provide a better estimate of forest fire and hydro outage hazard areas. This study aims to supplement the present knowledge of lightning and thunderstorm information for Manitoba by identifying lightning strike hazard areas.

1.2 THE STUDY AREA

The centrally located province of Manitoba extends from 49° N to 60° N. It stretches from approximately 95° W (in the south) angling northeastward to about 89° W (in the north) to a western limit ranging from 101° W (in the south) slightly angling northwestward to 102° W at the northern border. Covering 652 000 km^2, Manitoba includes a diverse range of geographic features, both natural and human. A mainly flat surface topography dominates the southern half of Manitoba with a line of remnant hills (rising from 300 m (1000 ft) to 600 m (2000 ft) above the plain) scattered in the western sector of the province marking the transition from a generally higher elevation west of these hills (second prairie level) to the lowland areas of central Manitoba (first prairie level). Elevation increases slightly at the far eastern sector of the province extending into the north following the lee side of Lake Winnipeg. Numerous lakes and rivers dot the province but Lakes Winnipeg, Manitoba and Winnipegosis cover the greatest areas. Rivers flow eastward and northward eventually draining into Hudson Bay (Figure 1.1).

Vegetation zones can also be roughly delimited (Figure 1.2) and are controlled by such factors as climate, topography, drainage and soil types. Boreal forest cover occurs over much of the rocky northern Canadian Shield corresponding with the cooler climate, the forest transitioning to sub-arctic forest further north as conditions are even cooler and drier. In the southern prairie, grassland dominates, diversifying into a mixture of grassland and woods

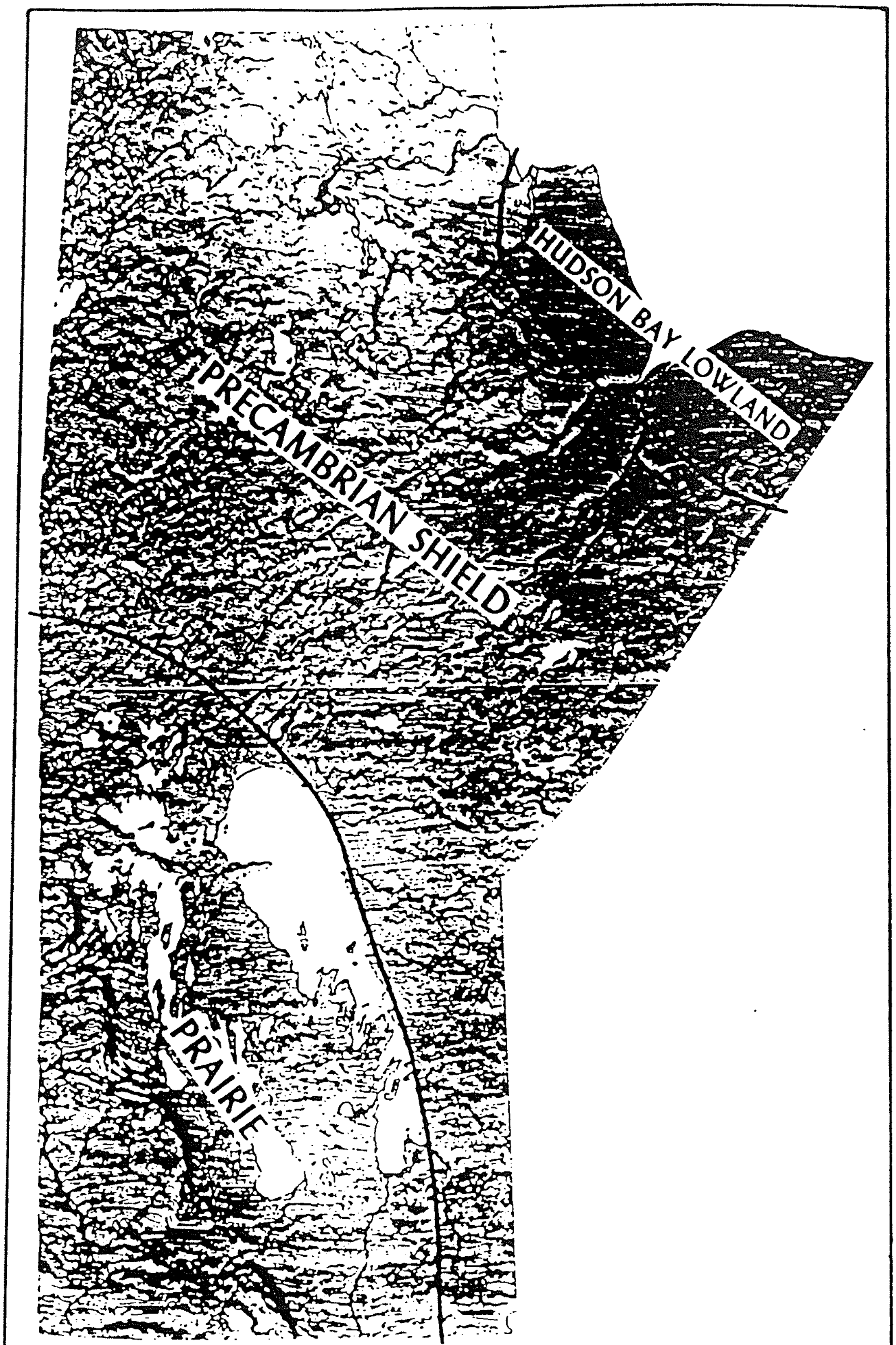


Figure 1.1: Physiographic Regions and Topographic Features of Manitoba. (From LaDochy, 1985)

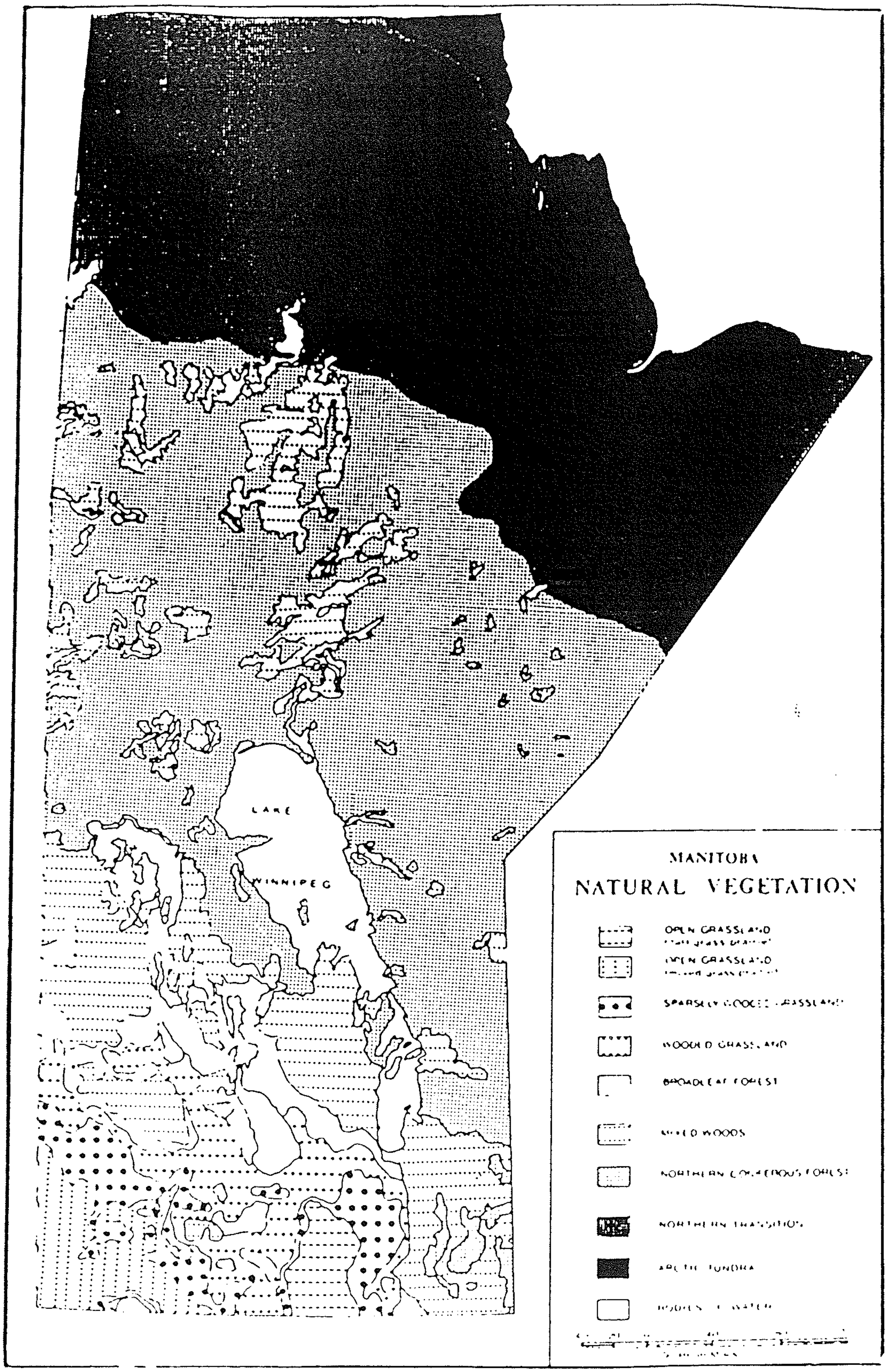


Figure 1.2: Vegetation Coverage in Manitoba. (Atlas of Manitoba, 1983)

between the prairie and forest as a result of the longer, warmer and relatively moister summer season. Most human settlement and development is concentrated in the southern sector of the province with more than 99% of the population found in the southernmost third of Manitoba (south of 53° N) and 55% in Winnipeg alone thus leaving large areas of the north mostly uninhabited.

1.2.1 MANITOBA WEATHER AND CLIMATE

Manitoba's interior position, distant from any ocean gives rise to a continental climate meaning that a great range of temperature occurs between winter and summer but precipitation occurs year round in some form. Manitoba receives most of its precipitation during the summer months with much of the precipitation coming from convective thunderstorms, especially in the southern part of the province where moisture content of the air and temperatures can become sufficiently high to induce instability. Table 1.1 displays long-term average maximum and minimum temperatures at Winnipeg and Thompson (representing southern and northern Manitoba) as well as extremes for the summer months.

Month	Average Maximum Wpg	Tho	Average Minimum Wpg	Tho	Extreme Maximum Wpg	Tho	Extreme Minimum Wpg	Tho
MAY	18.0	11.9	4.0	0.0	38.0	31.0	-12.0	-26.0
JUNE	23.0	19.2	10.0	5.1	38.0	31.0	-6.0	-11.0
JULY	26.0	22.6	13.0	8.7	42.0	36.0	2.0	-6.0
AUG	24.0	20.8	11.0	6.9	39.0	32.0	1.0	-4.0
SEPT	18.0	12.2	6.0	1.6	37.0	29.0	-8.0	-9.0

Wpg=Winnipeg (south) **Tho=Thompson (north)**

Table 1.1: Average Summer Maximum, Minimum and Extreme Temperatures (°C) (1951-80) for Northern and Southern Manitoba. (World Weather Guide, 1984)

South of 54° N average summer temperatures are 18° C or greater decreasing in a generally northeasterly direction. Between 54° N and about 58° N, average temperatures are around 15° C, falling to 10° C in the far northern sector of Manitoba (Figure 1.3). Summer precipitation varies from the southeast to the northwest with the southeast receiving an average of 305 mm (12 in) or more. North of the lakes extending northwestward amounts range from 254 mm (10 in) to 305 mm and less than 254 mm falls in the far northeast (Figure 1.4). Averages for temperature and precipitation, however, in a continental climate are less meaningful than for other regions because great variability can occur from day to day and from year to year.

The growing season in the southern third of the province, ranging from 80 to 120 days also varies following a south to north

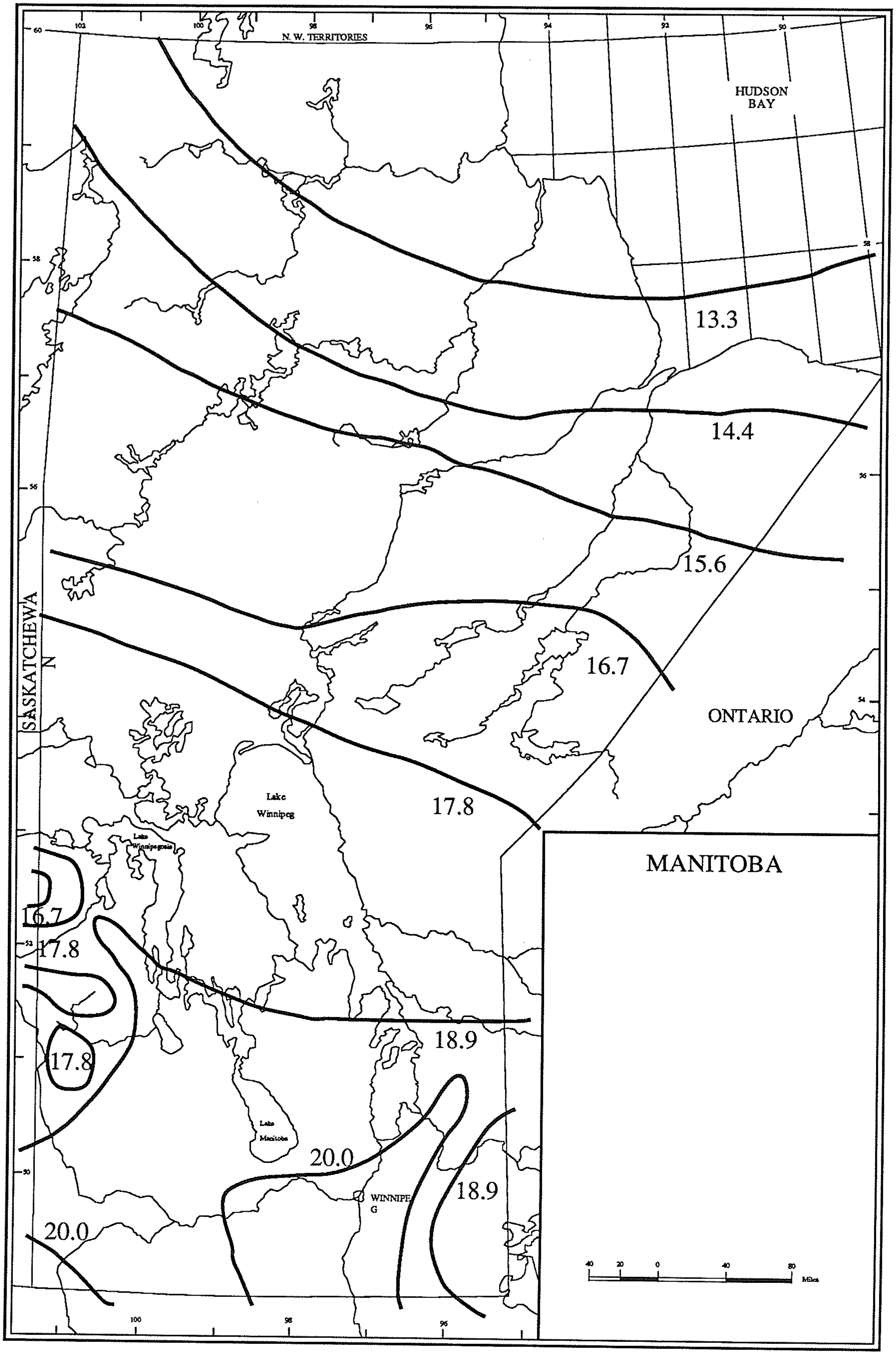


Figure 1.3: July Mean Daily Temperature (°C), 1951-80. (Source: Atlas of Manitoba, 1983)

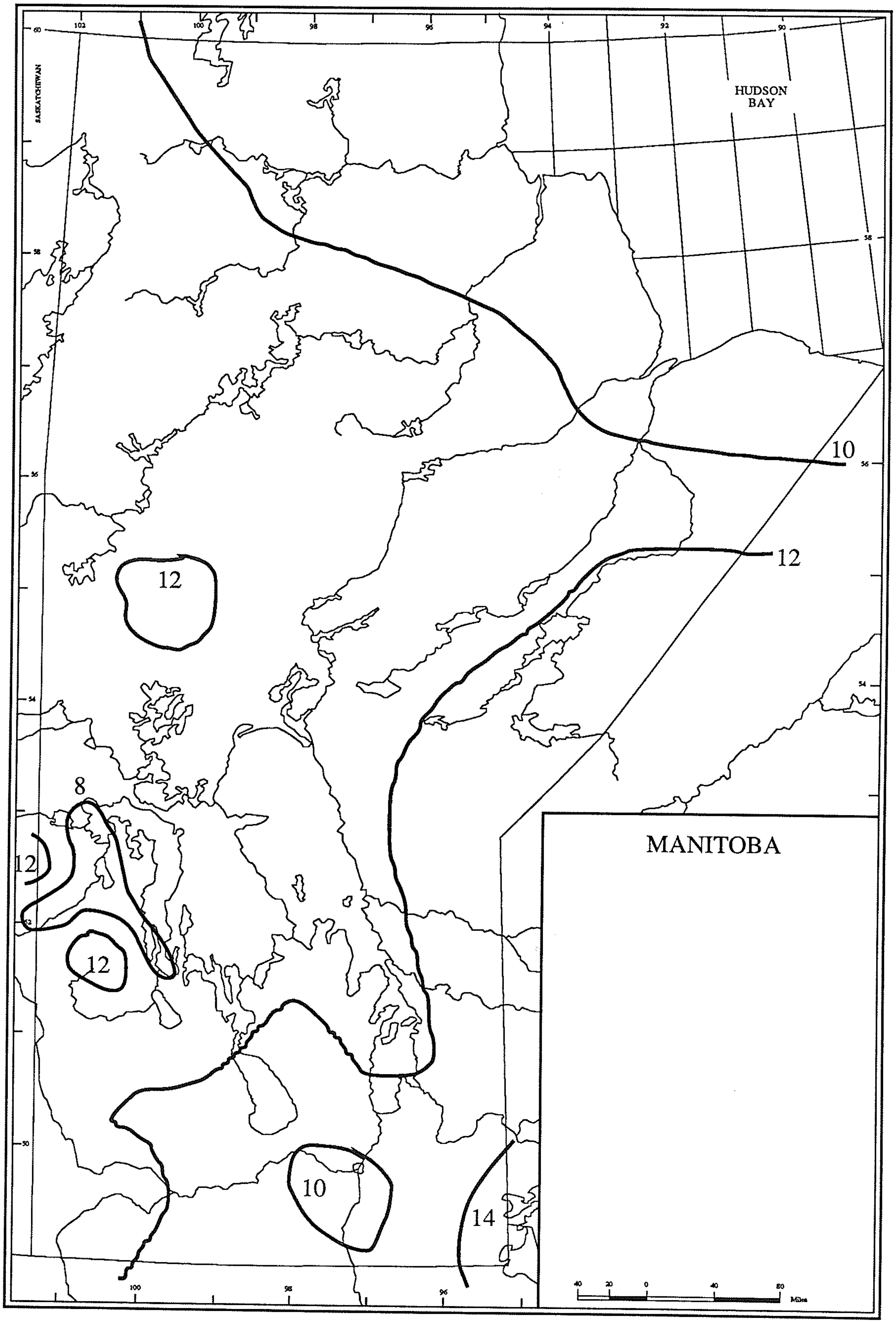


Figure 1.4: Mean Summer Precipitation (May to September) (inches), 1951-80.
(Atlas of Manitoba, 1983)

gradient, with the more southerly locations experiencing the longest season and growing time decreasing as latitude increases (Figure 1.5). Thunderstorm frequency usually increases as the summer progresses, following the seasonal heating increase with peak activity occurring late in June and early July. The southern part of Manitoba receives more thunderstorms than the north (Figure 1.6). Hail and tornadoes can occur during thunderstorms, both being more frequent during mid-June to Mid-August although other months have recorded significant hail or tornadic damage. However, since weather is so variable from year to year, the actual number of thunderstorms can vary significantly from year to year. Lightning, one component that always accompanies thunderstorms also varies from year to year and from thunderstorm to thunderstorm, as some storms can produce a great deal of flashes while others pass with hardly any activity.

1.3 THUNDERSTORM DEVELOPMENT

One definition of a thunderstorm is: "A local storm invariably produced by a cumulonimbus cloud, and always accompanied by lightning and thunder, usually with strong gusts of wind, heavy rain and sometimes with hail. It is usually of short duration, seldom over two hours for any one storm" (Huschke, 1959). In order for a thunderstorm to develop, three conditions must exist: air must be moisture-laden; some triggering agent must be present that will force the moist air to ascend (frontal or orographic lift or insolation heating, for example) and the atmosphere must be unstable so that

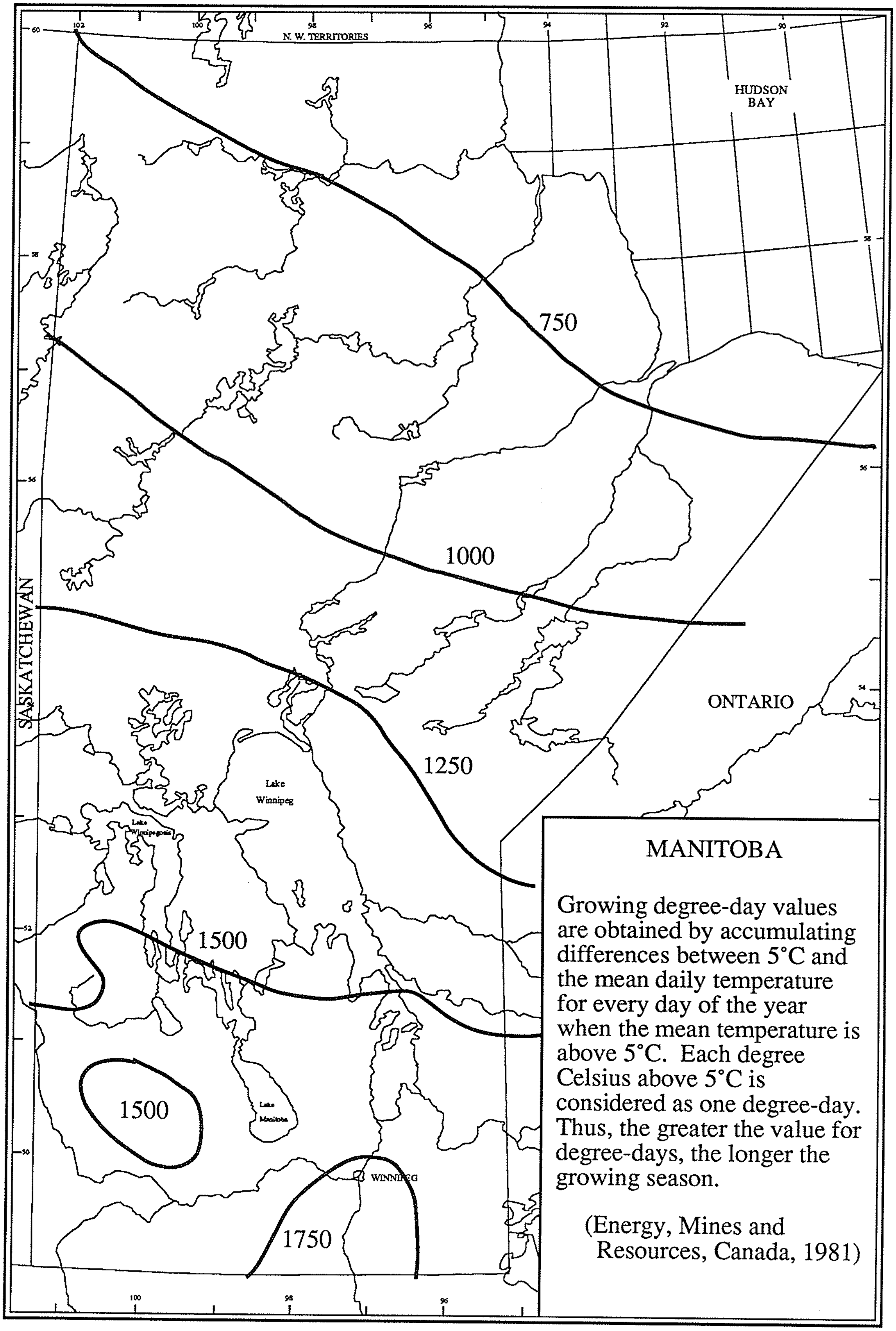


Figure 1.5: Annual Total Growing Degree-Days above 5°C, 1951-80. (Source: Climatic Atlas of Canada, Part 1, 1986)

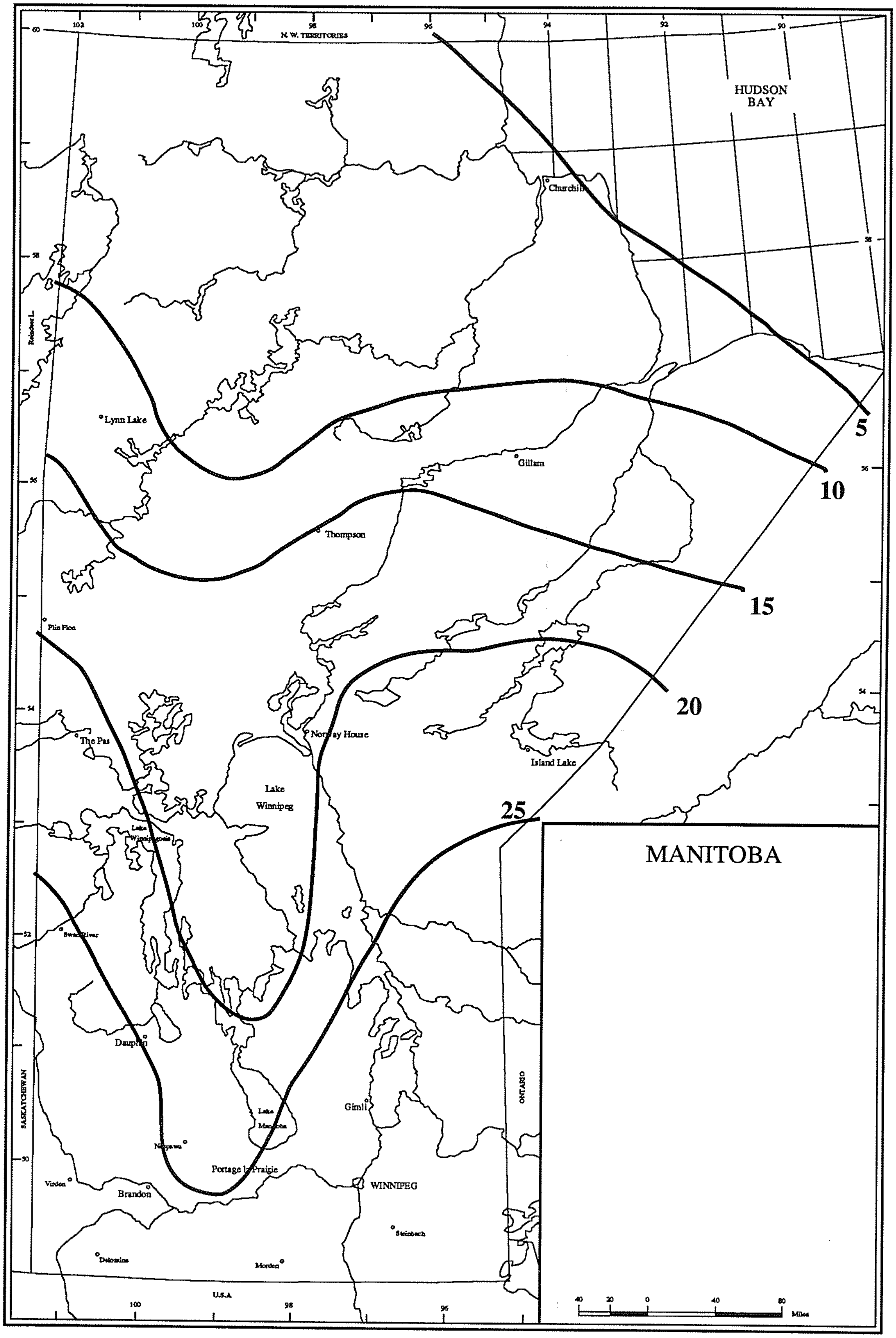


Figure 1.6: Distribution of Average Annual Number of Thunderstorm Days in Manitoba, 1951-80.
(Source: AES; from LaDochy, 1985)

the air parcel will rise to great heights in the atmosphere. When a parcel of unstable air rises, its temperature will not cool as quickly as the surrounding environment, therefore, the warm, surface air currents will rise freely replacing cool, dense air aloft. This is termed atmospheric convection.

A thunderstorm's life cycle can be broken into stages with distinct tropospheric conditions accompanying each stage, the three stage development cycle first outlined in detail by Byers and Brahams (1949). In short, during the cumulus stage, updrafts act to build the storm cloud; in the mature stage the storm is at its peak with intense vertical movements, possible heavy precipitation, cool gusts at ground level and maximum electrical activity; and finally in the dissipating stage, as updrafts diminish, the energy supply for the storm is cut off and the cloud dissipates through evaporation.

A thunderstorm cell can cover areas of 3 km in diameter to areas more than 50 km in diameter. A thunderstorm generally has a lifespan of about an hour but as the storm moves, in the direction of the upper winds in which it is embedded, fresh supplies of moisture-laden air can generate new cells to replace dissipating ones (Barnes, 1976). A thunderstorm, therefore, is comprised of numerous cells at various stages of growth or dissipation and thus can have a total duration of many hours.

A thunderhead can continue to grow vertically to a maximum height at the base of the stable stratosphere which suppresses air parcels from further upward growth. Cloud top heights, therefore, can reach an altitude of 20 000 m (60 000 ft) or more. At this level, vertical motion is deflected horizontally, resulting in the typical flattened cloud top (anvil-shape) of a cumulonimbus.

In Manitoba, scattered thundershowers can occur over broad areas because of intense local surface heating causing convection. This kind of storm is short-lived affecting a small area of similar temperature and moisture conditions (Maddox and Fritsch, 1984). Thunderstorms can also result when moist Gulf air travelling northwards collides with relatively cooler continental air creating a front as the warm (lighter) air is lifted. Frontal storms occur less frequently than localized thunderstorms but are more intense and move over a large area.

On a much larger scale, squall lines and mesoscale convective complexes can last for many hours or even several days. A squall line of storms may be born as more than one thunderstorm occurs along a front (actually 200 to 300 km ahead of the front), forming a line of storms. The storm moves quickly affecting "any particular location only for relatively short periods" but travelling over a relatively large area of hundreds of kilometres (Maddox and Fritsch, 1984). A mesoscale convective complex is comprised of many individual thunderstorms acting together to cause a particular atmospheric circulation that can be conducive to thunderstorm development. Horizontal extent can easily reach several hundred thousand square kilometres and because this system is slow-moving, with a lifetime of 12 to 24 hours or longer, it will affect any particular region for several hours (Maddox and Fritsch, 1984).

One classification of thunderstorms (Chisholm and Renick, 1972) based on size (horizontal extent) has categorized storms as single-cell, multi-cell and supercell, with the multi-cell occurring most frequently. A single-cell storm (covering about 3 to 10 km and lasting less than one hour) is of least importance because it is rarely associated with severe weather. A multi-cell storm (covering 30 to 50 km and lasting at least an hour, though this is highly variable) is comprised of numerous cells at varying stages of growth and decay producing significant amounts of precipitation, much electrical activity and gusty winds. A supercell refers to a "particular form of the mature stage of a multi-cell storm" (Browning, 1982). This individual cell in a thundercloud grows much larger, persists for a longer period of time and can produce unusually severe weather (hail, tornadoes or heavy rain).

A storm is classified as a thunderstorm after thunder is heard and, if thunder occurs, lightning in some form must also be present since thunder results from the heating and expansion of air caused by an electrical discharge.

1.4 THE LIGHTNING FLASH

Lightning can be defined as a visible electrical discharge produced during a thunderstorm. Different forms of lightning exist: the more common including *cloud-to-ground* flashes, *intra-cloud* flashes and *cloud-to-cloud* discharges. *Cloud-to-ground* strikes although occurring less frequently, are studied in greatest detail and are of most interest since they pose the greatest hazard to man.

Intra-cloud flashes, the most common, occur within a cloud between regions of positive and negative charges (Eagleman, 1983). Some other individual forms of lightning include: *ribbon lightning*; *sheet lightning*; *heat lightning;* an *air discharge*; a *bolt from the blue*; *ball lightning* and *St. Elmo's Fire* (see APPENDIX 1 for complete definitions of these types).

Before any electrical discharge can occur from a cumulonimbus storm cloud, a separation of charges takes place within the cloud. The base of the cloud acquires an excess negative charge while the top obtains an excess positive charge with the charges being carried on water droplets and ice crystals. When hydrogen and oxygen atoms lose or gain electrons (negatively charged particles), stability is lost transforming these atoms into positively or negatively charged ions. Exactly how storm clouds electrify has not yet been definitely determined as many hypotheses still exist (Illingworth, 1985; Uman, 1982).

The earth is normally negatively charged in relation to the atmosphere but when a thunderstorm passes over, the negative charge "in the base of the cloud induces a positive charge on the ground below and for several [kilometres] around the storm" (Wood, 1985). This occurs because like charges repel each other so the negative charges in a storm base repel the earth's negative charges thus leaving a preponderance of positive ions. As the cloud moves, its negatively charged bottom attracts positive charges from the ground below, the positive ground charges flow from the earth's surface up elevated objects (trees, buildings, towers) in order to "establish a flow of current" between the ground and the atmosphere (Wood, 1985). Since air is an insulator, a poor conductor of electricity, a free flow of current is not possible until huge electrical charges are built up. A visible flash of "lightning occurs when the difference between the positive and negative charges, the *electrical potential* [reaching millions of volts] becomes great enough to overcome the resistance of the insulating air and to force a conductive path for current to flow between the two charges" (Wood, 1985).

Each *cloud-to-ground* discharge is composed of a sequence of steps. The total discharge, made up of the invisible conductive path earthward and the visible release of energy upward (lasting from 0.2 to 0.5 seconds), is called a *flash,* with the *flash* broken down into several smaller components termed *strokes* (Uman, 1969). Each lightning *stroke* begins when electrons (the negatively charged ions) from the middle of the cloud are released to the cloud base which then frees them to the air immediately below, thereby ionizing the air. This discharge of electrons proceeds toward the ground in a series of *steps,* with normally three or four *steps* occurring per lightning *flash* (Handel, 1986). Once ionized, a column of air can become a conductive path termed a *leader.* The initial invisible downward path is a *stepped leader* where each *step* covers from 20 to 100 m and travels at a speed of 100 000 meters per second (Schlatter, 1987). The channel created by a *stepped leader* is normally branched with the majority of the forks not reaching anywhere until "eventually a path is developed from the cloud to the ground" (Eagleman, 1983). With the ionized path complete, electrons that were deposited along the channel begin to flow downward to the earth's surface. As the *stepped leader* approaches the ground, a current of positive charge starts upward from the ground (or elevated object) to meet the downward-moving current and "after they meet [five to 50 m above the surface], large numbers of electrons flow to the ground" and a visible *return stroke* "surges upward [toward] the cloud" along the path previously followed by the *stepped leader* (Loeb, 1980). As the *return stroke steps* traverse upward, the negative charge that was present in the channel is lowered to the earth. The bright streak discharging electricity from the ground to the cloud lasting a few tenths of a second then appears.

After the first discharge, generally there is still sufficient electrical charge in the cloud to generate several more lightning *flashes* along the first pathway. A *dart leader* which drains charges from higher areas within the cloud travels down the path, reionizes it and prepares the way for another *return stroke.* Unlike the *stepped leader,* the *dart leader* moves downward faster (2 million meters per second), it is without as many *steps* along the way and initiates a less branched *return stroke* (Uman, 1969). Thus a number of *return strokes* can be propagated from a single ionized pathway.

Thunder accompanies lightning flashes after air in the leader channel is rapidly heated by the release of ions downward. When the air is heated, it "suddenly expands from a few millimeters to a few centimetres in diameter" with "the shock waves resulting from the sudden expansion of air in the conducting channel [spreading] outward as thunder" (Eagleman, 1983).

1.5 CLIMATOLOGY OF MANITOBA THUNDERSTORMS BASED ON 1985 WEATHER STATION DATA

Thunderstorm occurrences are recorded by the AES via the meteorological stations scattered throughout the province. This study uses data collected at 11 first-order weather stations (Figure 1.7) which take hourly readings of variables and make synoptic observations.

Figure 1.8 shows the 1985 distribution of thunderstorm days in Manitoba. The most active area for thunderstorms is found in south central and southeastern Manitoba, thunderstorm days decreasing in both a westerly and northeasterly direction. Seasonal distribution of thunderstorm days, depicted in Figure 1.9, shows an increasing frequency from May with peak activity in July then a decrease in August and September and no recorded thunderstorm days in October. The 1985 season thus follows the general pattern of thunderstorm occurrences mirroring the increase and decrease of solar heating through the summer. Hourly distribution of 1985 thunderstorms also follows the long-term average diurnal distribution of thunderstorms (Figure 1.10) with minimum activity during the early daylight hours reaching peak levels in the later afternoon and evening. Activity still remains relatively high late at night.

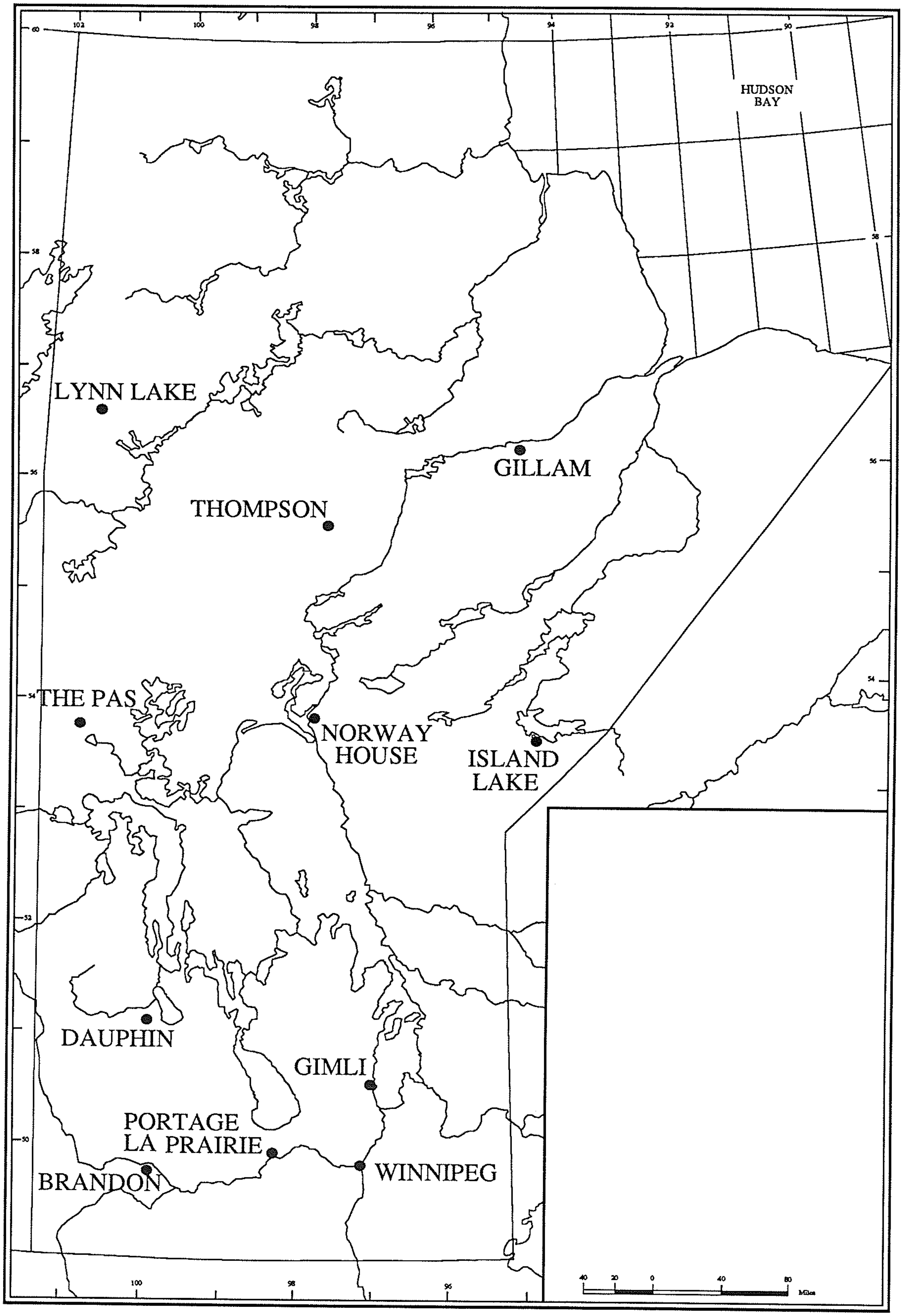


Figure 1.7: Manitoba climate stations used in this study.

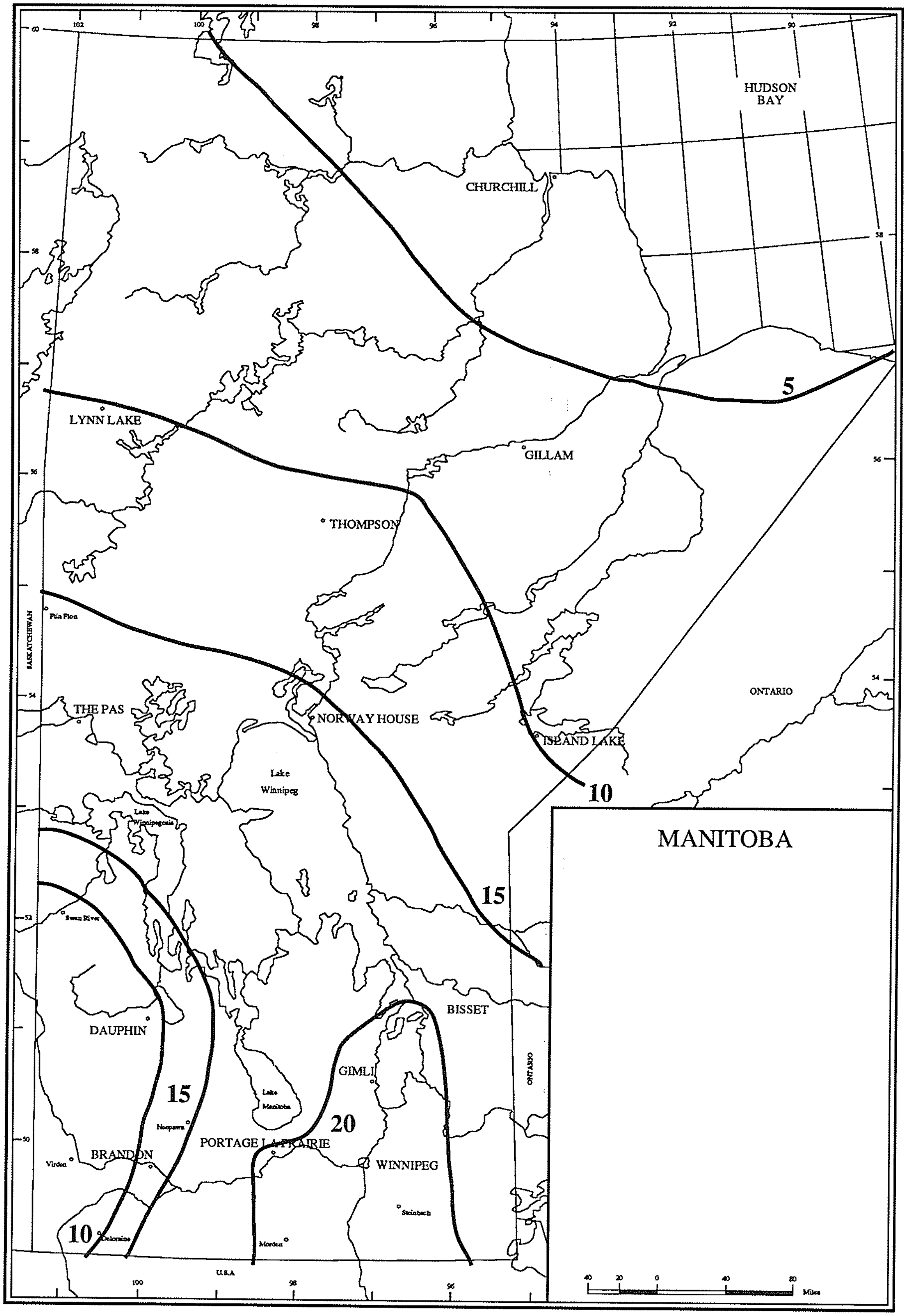


Figure 1.8: Distribution of Thunderstorm Days in Manitoba, 1985.
(Source: Atmospheric Environment Service.)

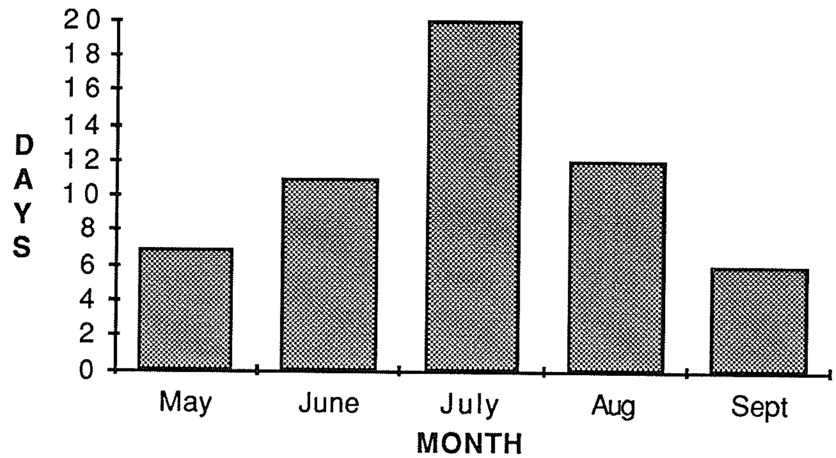


Figure 1.9: Seasonal Distribution of Thunderstorm Days in Manitoba, 1985. (AES)

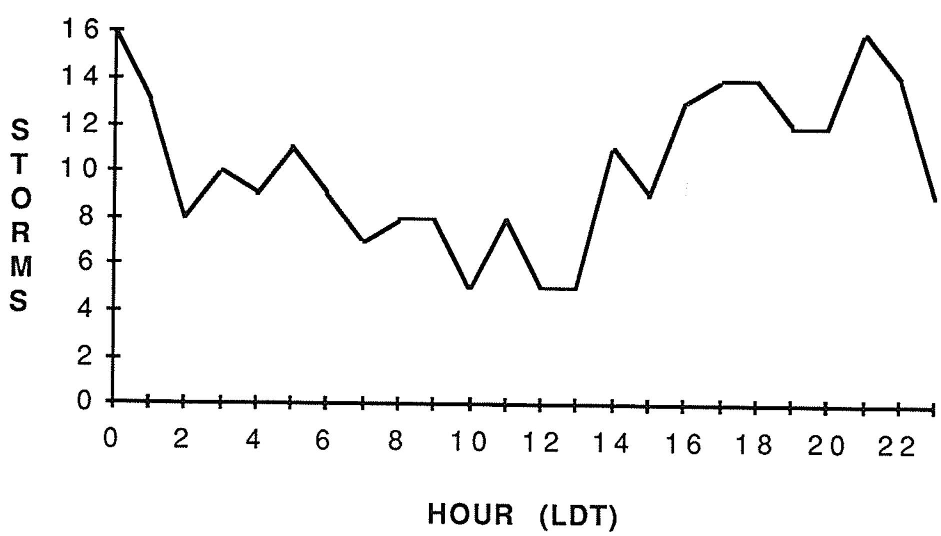


Figure 1.10: Hourly Distribution of Thunderstorms in Manitoba, 1985. (AES)

Because only a small number of points are available to record meteorological data covering such a large area, it is obvious that some additional method must be used to fill in as many gaps as possible. Proxy data are especially essential in order to identify thunderstorms more accurately in remote, unpopulated regions. Since a thunderstorm is reported when "(a) thunder is heard within the past 15 minutes, or (b) when overhead lightning is observed within the past 15 minutes and local noise level is such as might prevent hearing thunder" (Environment Canada, 1977), some thunderstorms may remain unnoticed by the AES if no one is around to hear thunder or see lightning. Proxy data, such as damage reports of lightning strikes, hail and tornadoes along with information on lightning-caused forest fires and transmission line interruptions "indicate the physical results of thunderstorms, not just the meteorological requirement of hearing thunder" (LaDochy, 1985). Now, cloud-to-ground lightning strikes can be mechanically detected and plotted thus directly locating an area of thunderstorm activity no matter where it is in the province. This study will examine the newly available lightning strike data and compare it with the AES weather station data, and proxy forest fire and hydro transmission interruption data. Lightning characteristics such as frequency and variability in time and space in Manitoba will be studied as well as synoptic weather conditions of a selected sample of lightning storms.

1.6 THESIS STRUCTURE

Chapter 1 has discussed objectives of this study in some detail and provides relevant general background information about Manitoba climate as well as definitions of a thunderstorm and different forms of lightning.

The various sources of data, their advantages and disadvantages are discussed in Chapter 2. Lightning detector data and some mechanical aspects of the equipment used to record cloud-to-ground strikes are explained. Previous research involving lightning strike data and applications are also discussed.

Spatial and temporal distributions of strikes are presented in Chapter 3 with the 1985 lightning distributions and variations being compared with available AES thunderstorm data.

Chapter 4 examines lightning characteristics and relationships with forest fires and power disruptions. High risk strike areas will be identified in this section.

Case study storms are studied in Chapter 5, where synoptic and other meteorological parameters compared with strike distribution and intensity.

A summary of findings and conclusions are discussed in Chapter 6, along with recommendations for future research with lightning detector data.

CHAPTER 2
DATA

2.1 LIGHTNING DETECTION EQUIPMENT

Conventional meteorological instruments, such as weather satellites and radar, can identify clouds of convective origin and regions of precipitation but not areas where lightning is occurring. Lightning detection systems that distinguish between cloud-to-cloud lightning and cloud-to-ground lightning flashes have been devised. Recently, a network of these lightning detectors which records the exact time and location of all cloud-to-ground strikes has been installed to monitor most of North America. Lightning detector networks provide a sophisticated and more accurate way of pin-pointing strikes on the ground thus making data obtained on this phenomenon's distribution in time and space more accessible and reliable. Two main manufacturers of lightning detection equipment are Lightning Location and Protection, Inc. (LLP) of Tucson, Arizona, and the Atlantic Scientific Corporation (ASC) of Melbourne, Florida, marketing the Lightning Position and Tracking System (LPATS). Both systems, along with some other methods of lightning detection, are in use throughout North America, with Manitoba utilizing the LLP system.

Cloud-to-ground lightning flashes emit strong, distinctive radio impulses which are unlike the more frequent intra-cloud flashes or any man-made signals. With the LLP system, positions of strikes are located by *direction finder* (DF) antennae that determine where a strike hit by a standard technique in radio direction-finding described in detail by Hiscox et al. (1984). A DF field station can operate on its own but ideally should be used in conjunction with other DFs. If only one station is used, it often will be working with weather radar to delimit areas of lightning and precipitation (thunderstorm potential). Various mechanical aspects of the LLP detection network, including detailed descriptions of equipment and electronic principles of how strikes can be detected are presented in a number of sources, including Maier et al. (1983), Krider et al. (1976).

In most cases, direction finders are incorporated in a large network of lightning locators, all connected with a microcomputer called the *position analyzer* (PA) that automatically accepts the relayed lightning data from the stations. DF antennae within range to pick up a cloud-to-ground radio signal determine the lightning azimuth angle, polarity (whether positive or negative charge is lowered to the ground), amplitude and number of return strokes per flash (up to a maximum of 14) before this information is relayed to the computer. The computer then analyzes the given data to determine the location of the strike (by latitude and longitude) displaying it in real-time. The DF measures magnetic direction about 200 meters above ground level, where the signal strength reaches its initial peak and various types of possible errors associated with the equipment are minimized. Current from horizontally built channels and branches are this way mostly ignored, "errors due to ionospheric reflections are eliminated" and the signal received is pointing "toward the ground contact point rather than some elevated position of the channel" (Hiscox et al., 1984). DFs are usually linked to the PA via local telephone lines but UHF/VHF radio or microwave links can also be employed.

A PA will handle data from several DFs if they happen to record the same strike. The location will be determined from the two DFs with the strongest recorded signals either by triangulation or, if a strike happens to fall close to the baseline connecting two DF stations, another formula, described in the *LLP Position Analyzer Manual,* is used (Lightning Location and Protection, Inc., 1982). Correction factors are pre-programmed in the computer and are implemented during the calculation of the strike location to take into account mechanical and natural irregularities such as vegetation cover or elevation variations. Hiscox et al. (1984) documents the methods of mathematical determination of location. Once data are received at the PA, they can be displayed on the computer screen for viewing during a storm and colour-coded to show temporal and spatial variation in time.

A map showing locations of strikes can be printed (Figure 2.1) and the information can finally be stored on magnetic tape for any future analysis. All lightning strikes can now be located for any day and time or specified region while the information is continually being updated. Previously, an incomplete distribution of lightning strikes could only be derived from several less reliable sources such as direct observation, photographic methods, radar techniques,

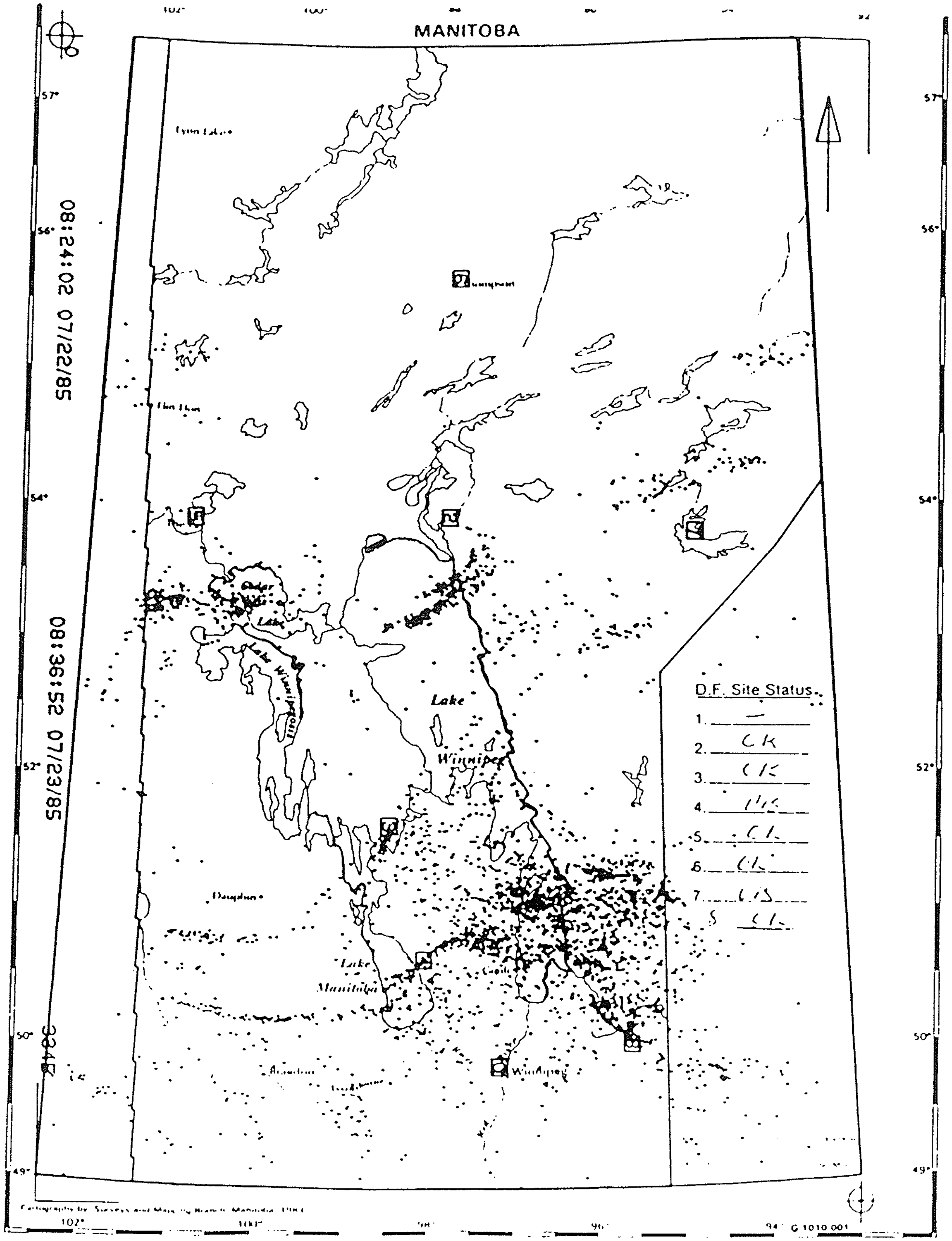


Figure 2.1: Example of a Map Showing Strike Locations.

evidence of lightning that caused damage to hydro transmission lines or evidence of lightning-caused forest fires. In these latter two cases, the data provide a frequency distribution of "damaging lightning strikes rather than all lightning strikes" (LaDochy, 1985).

Presently, Manitoba has seven DFs with the LLP network operating for six years (Figure 2.2). Of these, six are operational DFs since one of the units (#7 on map) has never functioned properly at its original location of Island Lake or in its present position at Bisset. Initially, the province started off with four DFs in 1982 placed at Gypsumville (#3), Lundar (#4), Norway House (#2) and The Pas (#5). Three additional units were added in 1984 at Thompson (#6), Island Lake (#7) and in the Whiteshell area (#8). However, as noted above, the DF at Island Lake never became fully operational due to various technical problems so was pulled out of operation in 1986. The former Island Lake unit (#7) was moved to Bisset and activated for the 1987 season but with problems still plaguing this DF, information provided for this area is incomplete and unreliable (Shipley, 1988).

2.2 PROBLEMS WITH DIRECTION FINDERS

Any lightning direction finding network is not perfect but the type of system described above is by far the best technology available to monitor lightning. Instrumental accuracy has been studied by Krider et al. (1980) with more than 98% of signals correctly detected as being cloud-to-ground strikes rather than cloud-to-cloud flashes or other signals. Accuracy of azimuth angle

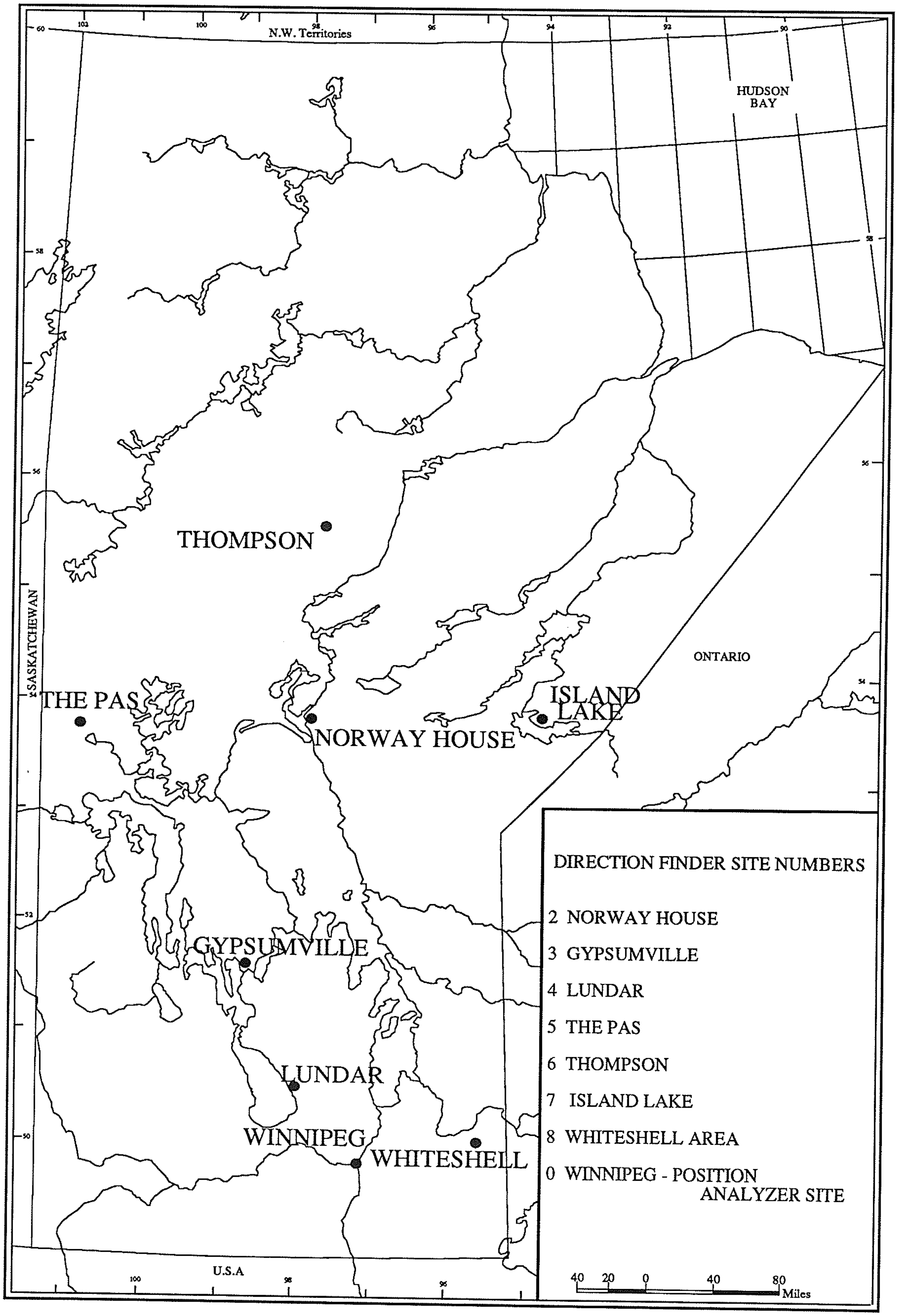


Figure 2.2: Direction Finder sites in Manitoba, 1985.

has been given as 1 to 2° or better (Krider et al., 1976) meaning that a strike's detected location usually falls within one to three kilometres of the actual hit. Similar percentages have been documented by Maier and Jafferis (1985), Peckham et al. (1984) and Uman et al. (1980). Droog (1988) tested the accuracy of Ontario DFs by comparing the number of known lightning-caused forest fires to their distances away from DF located lightning. He found that most fires did have lightning strikes within a couple of kilometres and 87% of the fires had lightning hit within 10 km indicating that over a 10 km distance, strikes are located accurately enough for fire monitoring. Accuracy is difficult to improve since a pre-programmed calculation is used to determine location and as yet a better algorithm has not been identified (Hiscox et al., 1984).

Other external factors do, however, affect detection accuracy and efficiency. Efficiency of a network refers to the percentage of cloud-to-ground strikes that are actually detected by DFs. Individual DFs will display varying degrees of efficiency depending on location because biases exist in some areas due to the positioning of DFs and different sites have various levels of detection capability in specific directions and at different distances. Generally, as distance increases away from DFs, a lower percentage of strikes are detected but the absolute values depend on site and direction. Efficiency can be improved by attempting several modifications of the site including clearing ground around a DF of trees or other barriers that may block lightning signals, improving grounding around the electric field antenna, minimizing the electric-magnetic field antennae ratio, or as a last resort, relocating the DF site (Droog, 1988).

A number of DF efficiency studies have been undertaken with a range of percentages reported for the different networks. For example, in the Tampa Bay area of Florida, Peckman et al. (1984) found that 75% of strikes were detected between a 25 and 50 km range of any particular DF, 70% for 50 to 70 km, 63% at 75 to 100 km and 55% at distances of 100 to 150 km. Other networks in the United States have also been studied for efficiency by Orville et al. (1987), Reap (1986), Maier et al. (1985), MacGorman et al. (1984b) and Krider et al. (1980), with similar results of fewer strikes detected as distance increased away from DFs. A Canadian test of efficiency for the Ontario network found that DFs detected about 80% of strikes within a 350 km range (Droog, 1988).

Directional efficiency is a local phenomenon individual to each DF. Causes of different efficiencies are not fully understood. Testing of efficiency can be done several ways, details of procedures being illustrated in Orville et al. (1987) and Peckham et al. (1984).

Although Manitoba's lightning locating network has not been formally studied for efficiency and accuracy ratings, estimates of 80% of all strikes being detected seem reasonable (Shipley, 1988). Some local problems have also been identified with Manitoba's network and these are discussed in the following section.

2.2.1 PROBLEMS WITH MANITOBA DIRECTION FINDERS

Each DF relays information to the Winnipeg PA via either a direct link or by transferring signals to another medium for transmission from there. Three northern stations, The Pas, Norway House and Thompson are interconnected with telephone lines. Signals from The Pas and Norway House are transmitted to Thompson from where the information of all three sites is sent to Winnipeg via a microwave tower. In the Interlake, Gypsumville receives signals from Lundar via phone lines, transmitting signals from both DFs to the Winnipeg PA, again by way of a microwave tower. Island Lake first sends signals to a microwave tower where they are transferred to phone cables. Data from the east (Whiteshell and Bisset) are relayed directly through phone cables only.

At Island Lake where a signal was first sent to a microwave tower, then transferred to land-line phone cables for transmission to Winnipeg, the DF signal could not be clearly transmitted to the PA computer because of the extent of electronic interference. It is not known exactly why so much 'noise' occurred in this area but it occurred often enough for many of the DF signals to be lost in a jumble of other signals. This DF was finally moved to a new site at Bissett in 1987 in an attempt to rectify the problem.

However, at the Bisset site, a communication problem again developed in which DF signals often became lost during transmission to Winnipeg through phone lines. In this situation, interference can be explained by the amount of activity on the phone lines. Here or at any other rural setting, many party lines are in service, thus much activity exists on the transmission lines, obviously undesirable for data transfer. An example of how a DF signal can be lost occurs if three DFs picked up a cloud-to-ground strike and the communication lines of one unit are 'noisy'. Location data then would actually be provided from only two DFs, thereby creating a situation where there is no accurate way to cross-check the location of a strike since triangulation could not be applied with one station unable to communicate.

Figures 2.3a and b are two examples of inaccurate locating of strikes by DFs. An apparent west-east orientated straight line of strikes (Figure 2.3a) arises from a malfunction in the north-south loop of the DF antenna resulting in readings only in west and east directions (Hopko, 1988). The phenomenon of arcing (Figure 2.3b) also occurs occasionally. This type of error can probably be classed as a "baseline" error, where the strikes are located near a line connecting two stations with no third station able to triangulate. An arc of strikes is visible extending from the Lundar DF in Figure 2.3b. Causes of this arcing phenomenon in Manitoba are not definitely known but are most likely due to site errors. Site errors in angle measurements can be caused by nearby objects such as power lines or buildings. It is also possible that these arcs are caused by misalignment of antennae to true north (Hiscox, 1988). In general, little interaction has occurred between Manitoba and the LLP Inc. on the operation and maintenance of this network.

Besides the potential for communication problems leaving gaps in coverage, Manitoba does not have a reliable archiving system in

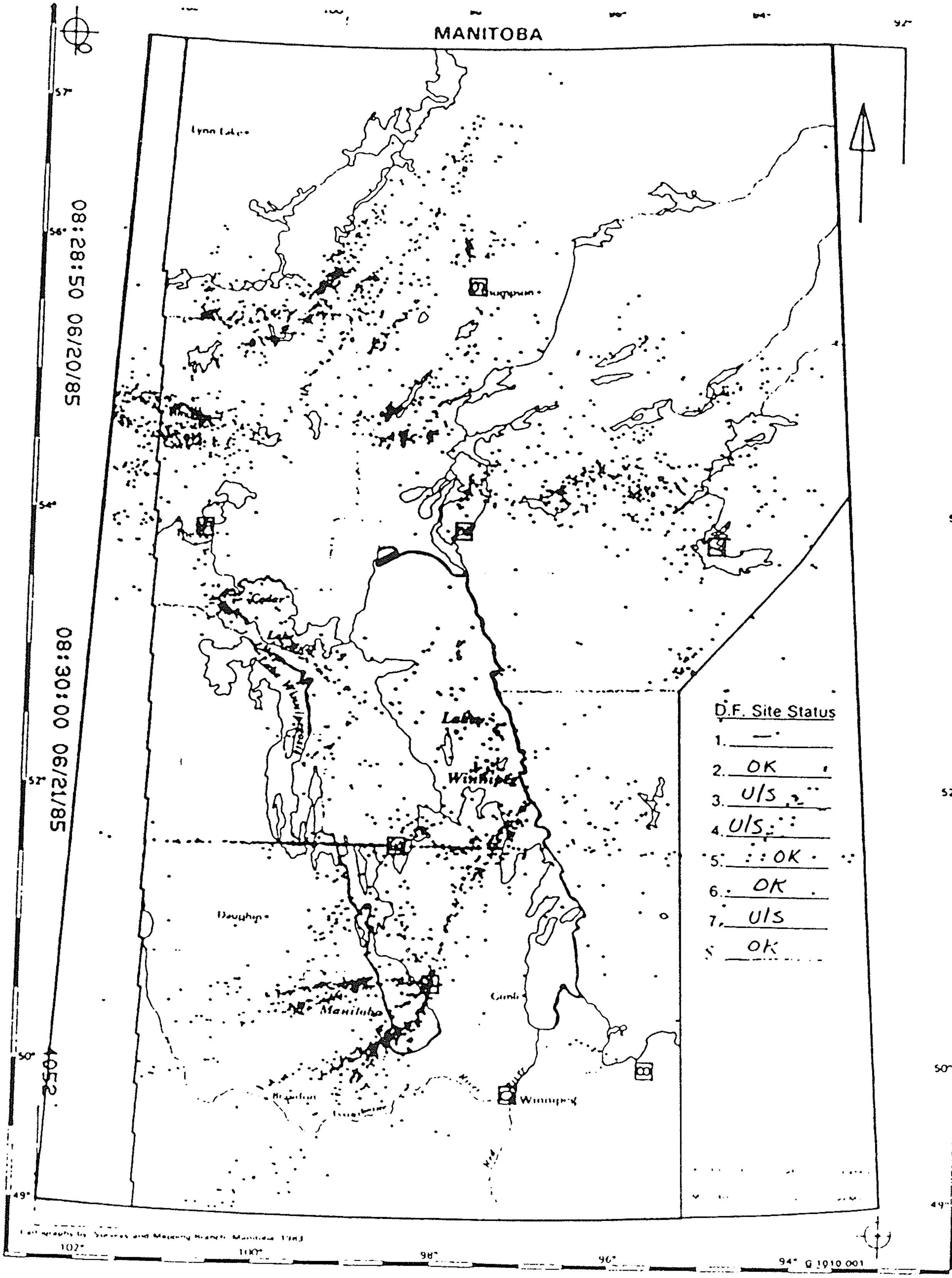


Figure 2.3a: Direction Finder Error Example: Antenna Malfunction.

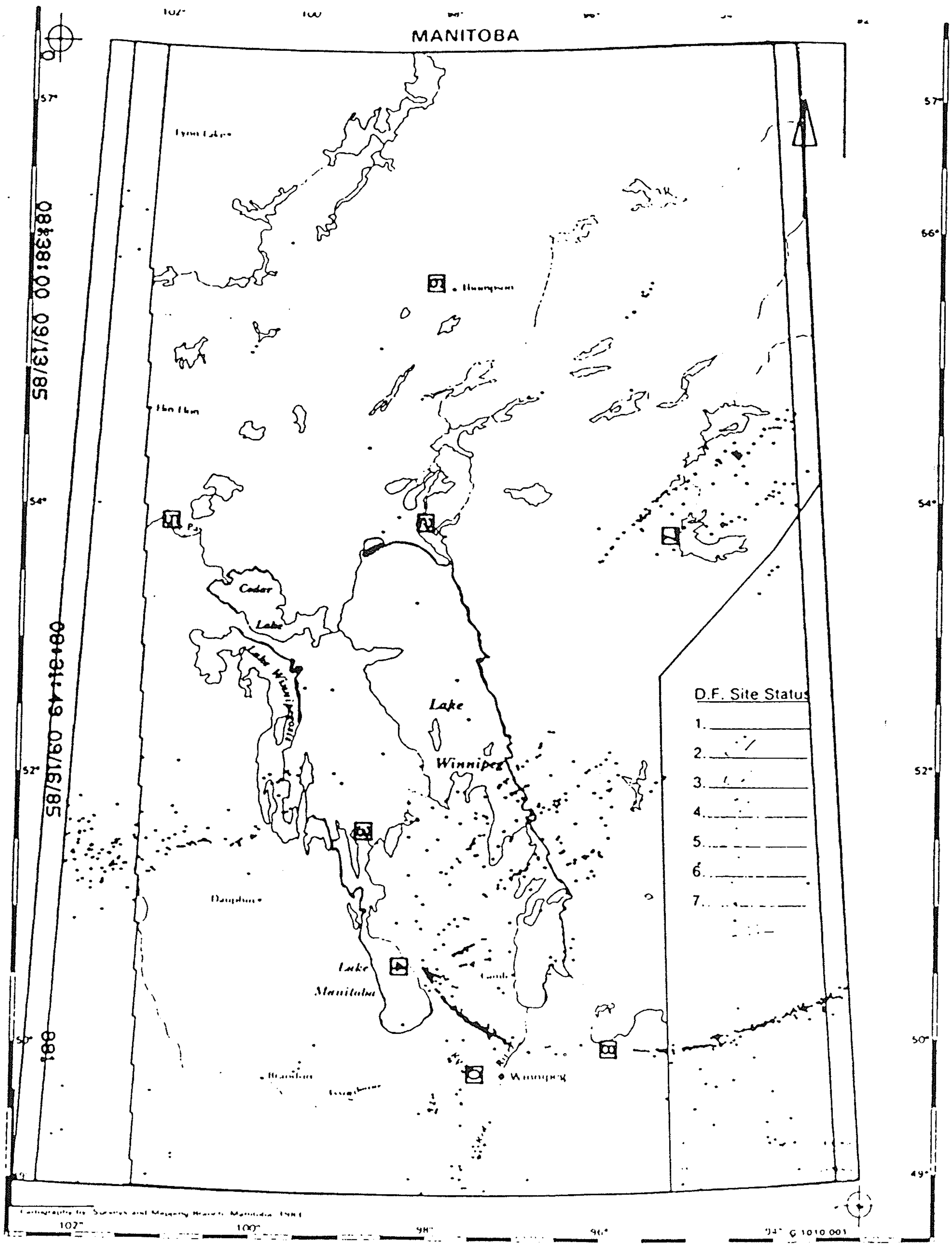


Figure 2.3b: Direction Finder Error Example: Arcing.

place to store transmitted lightning data for future use. The Columbia 300 automatic four-track reel tape recorder that records the relayed lightning information is not an efficient mechanism for this purpose because it must be manually set after each track runs out of space. Consequently, if the tape is not reset (either by not being monitored closely or because no one was present to perform the duty as is the case after working hours), a complete set of data will not be recorded in tape form. Even though the past lightning data is stored in the computer's memory and can be viewed on a screen or printed on a hard copy map in the form of dots showing lightning strikes, it is not possible to retrieve original numeric values of azimuth, polarity, amplitude, number of return strokes per flash or the determined latitude and longitude. For the Natural Resources Fire Protection Division (the keepers of the LLP system in Manitoba), in most cases, it is sufficient only to view the positions and times of strikes on maps in real-time. Other users wanting to study past records experience some difficulty in this respect, however. The tape recorder itself was not operational until 1985 even though the entire system was introduced in 1982 since no instructions on use of the recorder were supplied to the Fire Protection Division. For 1986, taped information does not correspond with available hard-copy maps, the computerized data lacking most of the 1986 season's strikes and it is not known how and why this happened (Shipley, 1988). Blank tapes for the 1988 season were neglected to be ordered so no computerized record will be available (Hopko, 1988). Thus, because of the sporadic nature of the long-term storage, this study concentrates on the 1985 season (May to September) as it is the season that yielded the most complete and reliable record of lightning occurrence over the province.

As noted earlier, DFs can distinguish between negative and positive strikes. This innovation was developed in 1984 after researchers recognized the need to distinguish between the two kinds of strikes. In 1984, when the three new DFs were added to the Manitoba network, they came equipped with the ability to identify discharges lowering positive charge or negative charge to the ground. The original four units installed in 1982 were also equipped with this capability in 1987. Throughout the three year interval when three units could discriminate between positive and negative strikes and four units could not, the polarity of a discharge was still available since the three DFs with the feature were not together in a triangulation pattern. In other words, of three DFs that located a particular strike, at least one DF had the capability of identifying polarity.

In Manitoba, the DFs relay data normally from May to October, assisting in fire weather forecasting at the Forestry Management Branch, Fire Protection Division and at the Environment Canada weather office. The *long baseline* lightning locating system is in place here because it is best suited for covering large areas with the highest accuracy and efficiency possible. The baseline in a network of DFs is defined as the straight-line distance between any two DFs. DFs should be spaced about 150 to 250 km apart to provide good coverage. A *short baseline* lightning locating system where DFs are spaced 25 to 100 km apart is established if highly accurate lightning data are required, usually for operations sensitive to lightning damage such as electric companies, television broadcasters, military bases and computer facilities (LLP Inc, 1984).

When DFs are closer together, the determination of the angular location of strikes is much more accurate. For example, if "*direction finders* are [80 km] apart, the displayed lightning strike locations are usually within [0.8 to 1.6 km] of the actual location" (LLP Inc, 1984). If a strike happens to fall close to the baseline connecting two DFs, location accuracy is poor because azimuth angles are complimentary and may not intersect at only one point (baseline error). Either system can be easily expanded by adding more DFs or PAs to disseminate information to other interested parties.

2.3 THE LIGHTNING DATA

Magnetic nine-track computer tape holds the 1985 lightning strike data transferred from the 3M cassette cartridge used in the PA. Various information in the form of rows of decimal numbers and hexadecimal digits are present in the data with two types of output possible. One line of data begins with a control character (%) and is followed by a varying number of rows (not headed with any control character). That is, a longer line (45 characters total) starting with a control character is always followed by a number of shorter lines (24 characters total). Information provided by the first (control character) line is used in the analysis because this is the information that has been processed by the PA computer into easily readable numeric format whereas the lines underneath (with no control character) are raw direction finder data (decimal and hexadecimal numbers). Figures 2.4a and b detail sample output showing a line of PA data and raw DF data, respectively.

As stated before, the first character from the position analyzer line (Figure 2.4a) is a control character (column one). The next 15 characters (columns two to 16) give the time and date of a strike: characters two and three represent the hour of the day; characters four and five indicate the minutes; six and seven are the seconds; and finally, milliseconds are given by the eighth, ninth and tenth characters. Month, day (each given by two characters) and last two digits of year are shown by the eleventh and twelfth; thirteenth and fourteenth; fifteenth and sixteenth characters, respectively. In the example shown in Figure 2.4a, a strike occurred at 1400h, 26 minutes, 56 seconds and 452 milliseconds on May 23, 1985. Following the time and date of a strike, a flash sequence number (in this case, it is 98) is printed with as many as five character spaces (columns 17 to 21). A flash sequence number is just a count of the total number of strikes recorded by all DFs for each day and is reset to zero at midnight. Latitude and longitude of the strike are listed in columns 22 through 37, both being composed of a sign (positive or negative), degrees (two or three characters), minutes (two characters) and seconds (two characters). Latitudes

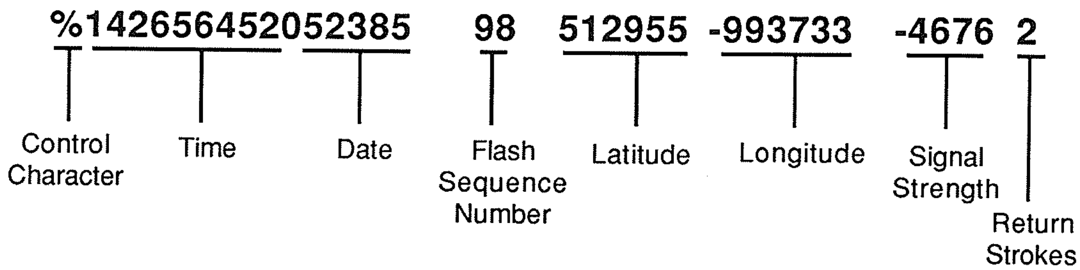


Figure 2.4a: Sample Position Analyzer Output.

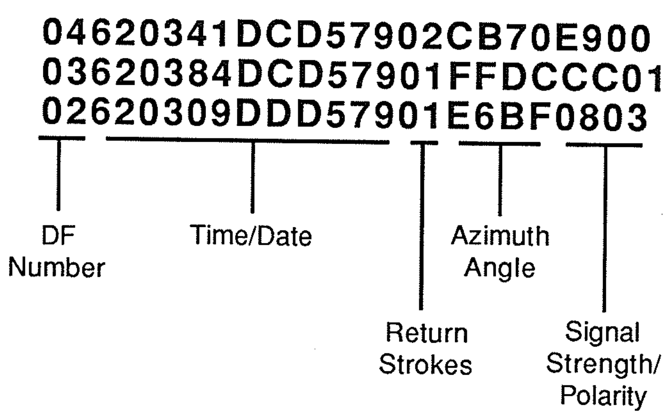


Figure 2.4b: Sample Direction Finder Output.

are positive in the northern hemisphere (0 to 90° North) and negative in the southern hemisphere, so obviously all the latitude data for Manitoba will be positive. The absence of a sign indicates a positive value and thus a latitude in the northern hemisphere. Longitudes are positive in the eastern hemisphere (0 to 180° East) and negative in the western hemisphere (0 to 180° West) so all longitudes in Manitoba begin with a negative sign indicating a western hemisphere locale. In the example (Figure 2.4a), a strike is located at 51°, 29 minutes, 55 seconds North latitude and 99°, 37 minutes, 33 seconds West longitude. The next six spaces (columns 38 to 43) are assigned to the signal strength which is also headed by a positive or negative sign with a positive sign given if the return stroke of a flash lowers positive charge to the ground and if negative charge is lowered, a negative sign is recorded. Negative charge will be lowered by the majority of return strokes. Numbers following the polarity sign indicate signal strength of the first stroke in a ground flash, the value being normalized to 100 km. Values must be normalized in order to take into account the varying distances strikes occur away from DF antennae. If a strike happens to land particularly close to one antenna, then its detected signal at that antenna will be highly amplified. Signal strength is thus standardized to what the strike's strength value would be at 100 km from a DF station. The value is determined by the PA after location is calculated and is proportional to the peak current in the first stroke (Uman, et al., 1975). Finally, the number of return strokes for a flash is noted in the last two spaces (columns 44 and 45), the most common amount being equal to one, two or three return strokes per flash. As many as 14 return strokes can be recorded.

Raw DF data (Figure 2.4b) from any field station that happened to detect a strike is closely related to the information compiled by the PA computer. With this example, three DFs picked up the electromagnetic signal. The first two numbers (columns one and two) indicate which DF picked up the electromagnetic signal. Each DF site of a network is assigned a number (in Manitoba, DFs are numbered two to eight) so that it is known which DF detected any particular strike. Output is recorded as DF site number minus one, thus in the example, site 05 is actually referred to as DF #4 in the raw output, site 04 is labelled as #3 and site 03 is #2. Columns three to 14 (hexadecimal numbers) are time variables, with 09DD being the minute of the day, B3AC the millisecond of the minute and D579 the day of the century. Number of return strokes (decimal numbers) found in columns 15 and 16 detected by any particular DF is listed, the total (greatest number recorded) being transmitted to the PA. A signal's azimuth angle is recorded, again in hexadecimal (columns 17 to 20) by all direction finders that happen to be within range to detect a signal and the angles recorded will be used to calculate the exact position of a strike (by latitude and longitude). The final four characters indicate DF signal strength and polarity.

The 1985 lightning detection season, spanning late May to the beginning of October recorded tens of thousands of cloud-to-ground lightning strikes and return strokes. It is possible for the detection network to operate year round but this is not necessary in Manitoba since the probability of lightning is highest during the summer months and any hazard to environment or man is also greatest at this time. A total of almost 68 000 'valid' cloud-to-ground strikes were recorded for the 1985 season after around 2 000 observations were eliminated because they did not appear in the correct format. Unusable information can result from a number of errors: DFs did not detect, record or transmit data properly; the PA could not work with transmitted data or itself malfunctioned; and finally, computer error during extraction of data from the tapes is also a possibility.

2.4 RESEARCH APPLICATIONS OF DF LIGHTNING DATA

Lightning data from networks of DFs have already been used to monitor and study a wide-ranging spectrum of phenomena. One of the first applications involved the detection of lightning-caused forest fires. The United States Bureau of Land Management set up the first large-scale operational, commercial network in 1976 monitoring the western U.S. using data to determine likely locations of lightning-caused forest fires (Krider et al., 1980). Canadian networks have been installed since that time, their primary function also being forest fire detection. Although early warning forest fire detection is still the major application of Manitoban and Canadian lightning DF data, other important applications have been found. Most of the research in the area is still being undertaken in the U.S.

The second largest American integrated network which became operational in the early 1980s monitors cloud-to-ground strikes in the eastern U.S., this data being disseminated to electric power companies, the National Weather Service and a number of private agencies. Authorities responsible for protection of lands and the protection of electrical generating stations as well as power transmission networks have relied upon DF data displaying locations of strikes for early warning purposes. Potential sites for lightning-caused forest fires or transmission interruption problems can be pin-pointed faster and managed more efficiently as a "rapid deployment of resources to protect property, fight fires and restore service" can be achieved (Newhouse, 1987). If a forest fire is reached in its early stages "both the size of [a fire] when first detected and the suppression cost" can be greatly reduced (Krider et al., 1980). Electrical utility companies can benefit from DF lightning data by using it to monitor field outposts and plan transmission networks (Newhouse, 1987; Fisher and Krider, 1982).

The first studies to look at synoptic conditions as they relate to different levels of lightning activity (Goodman and MacGorman, 1986; Orville et al., 1983) were initiated within the U.S. east coast network. Comparisons of lightning data with other available meteorological observations of storms provides insight to basic principles of lightning occurrence within thunderstorms (Orville, 1987). Lightning is an extremely variable phenomenon, differing in characteristics from region to region, storm to storm and even within a single storm. Lightning climatology studies are, therefore, becoming an integral part of thunderstorm research because they provide a convenient means of obtaining a comprehensive picture of lightning activity over any area. Better detection of convective activity is possible especially in areas which are lacking in surface and radar observations or are obscured by other meteorological or topographical features (Edman, 1986; Reap, 1986). Other research includes studies on the nature of lightning as it is concerned with atmospheric physics (Williams, 1985; Rust et al., 1985). Electrical activity in tornadic storms (MacGorman et al., 1984b; 1983), in mesoscale convective complexes (Horsburgh et al., 1983) and comparisons between multi-cell and supercell thunderstorms (Goodman and MacGorman, 1986; Maier et al., 1983) have also been documented. Information on positive cloud-to-ground strikes is available in Beasley (1985) and Rust et al. (1983).

Numerous studies have been undertaken using DF data to evaluate cloud-to-ground lightning characteristics in different areas. Reap (1986) using the DF data for the western U.S. looked at geographical and temporal distribution of strikes along with magnitude of activity and relationships between these distributions and topography. Similar lightning data have been used by Lopez and Holle (1986) to determine spatial and diurnal variability of strikes in Colorado and Florida. Diurnal variations of lightning over the Florida peninsula were compared with standard weather observations of thunder (L. Maier et al., 1984). Orville et al. (1987) and Peckham et al. (1984) used LPAT lightning data to identify various behaviours and relationships for the northeastern U.S. Lightning strike densities have been mapped for the contiguous U.S.

by MacGorman et al. (1984a). Distributions of lightning in space and time derived from these studies can give information of prevalent lightning hazards.

Lightning data from detection networks prove to have a number of advantages over traditional recording methods. Since DF lightning data have a higher resolution in time and space, it is a valuable source of thunderstorm information. Using DF equipment, thunderstorms can be identified sooner, even in remote areas allowing forecasters to pin-point locations, track motions and monitor time-development of storms more accurately, thereby filling gaps in manual observation data and improving interpretations of other available weather data. Short range forecasting of severe lightning storms is possible after correlation of frequent lightning activity with meteorological variables (Rust et al., 1985; Taylor et al., 1984) and identification of activity with certain radar echoes and satellite image features (Holle et al., 1983; Geotis and Orville, 1983; Orville et al., 1982). Locations of ground strikes in real-time "have [also] proved useful in the operational duties of [American] air traffic controllers, weather forecasters, fire managers and personnel of electric power companies" (Federal Coordinator for Meteorological Services, 1987).

DF data provide the best way to observe and record lightning over large areas. By studying the frequency and spatial and temporal distribution of the phenomenon, a more complete explanation can be found to interpret any variability observed. Networks of lightning DFs provide the most reliable data to date and are convenient to use for examining various characteristics of flash and storm activity.

2.5 AES WEATHER DATA

Meteorological data collected by conventional climatic stations have been used and compared with lightning strike data from the LLP network. Thunderstorm day and hour data for 1985 collected at first order climatological stations (Figure 1.7) provide a conventional picture of thunderstorm activity in Manitoba. Whereas a thunderstorm day refers to a 24 hour period in which thunder was heard sometime during that day at a given weather station, a thunderstorm hour is one in which thunder was heard sometime during a one hour period. Therefore, it is possible for more than one thunderstorm to give several thunderstorm hours but be represented as one thunderstorm day. Using these data to infer lightning characteristics of an area is not practical for several reasons. The duration of lightning activity cannot be derived from the number of thunderstorm days or hours. The progression of lightning intensity through time cannot be taken into account. Cloud-to-ground strikes are not distinguished from other lightning forms. Since a thunderstorm day or hour is recorded at a given station if thunder is heard (usually within a range of one to 20 km from a station), it is possible that some lightning activity may be missed if a storm occurs outside this 20 km range (MacGorman et al., 1984b). In this study, lightning DF data is compared with the standard measurements of thunderstorm days and hours. For case study, most active 1985 and 1986 lightning storms' synoptic features are analyzed and compared with strike distribution. Some meteorological observations (temperatures, dewpoints and precipitation) are also compared with lightning frequency and distribution.

2.6 PROXY DATA

Two forms of proxy data can be used to locate cloud-to-ground strikes: forest fire occurrences and hydro transmission line interruptions. The Manitoba Department of Natural Resources, Fire Protection Division keeps a monthly record of forest fire locations according to forest districts (Figure 2.5). This record contains the time the fire was started or reported, total land area burned, cause and suppression costs. If a fire was lightning-caused, as is the case in almost 50% of forest fires in Manitoba (Ramsey and Higgins, 1982), it will be examined in detail along with lightning strike data. Comparing spatial and temporal distributions of forest fires with cloud-to-ground strike patterns can provide some insight for determining lightning hazard areas in Manitoba and reasons why these areas have potential for lightning problems.

Examining power failure data to determine lightning hazard areas is also useful because power transmission lines directly hit by lightning or within close proximity of a strike "show specific characteristics which leave no doubt as to their cause" (LaDochy, 1985). Manitoba Hydro has also delimited the province into regions (Figure 2.6) with each region being split into smaller, more

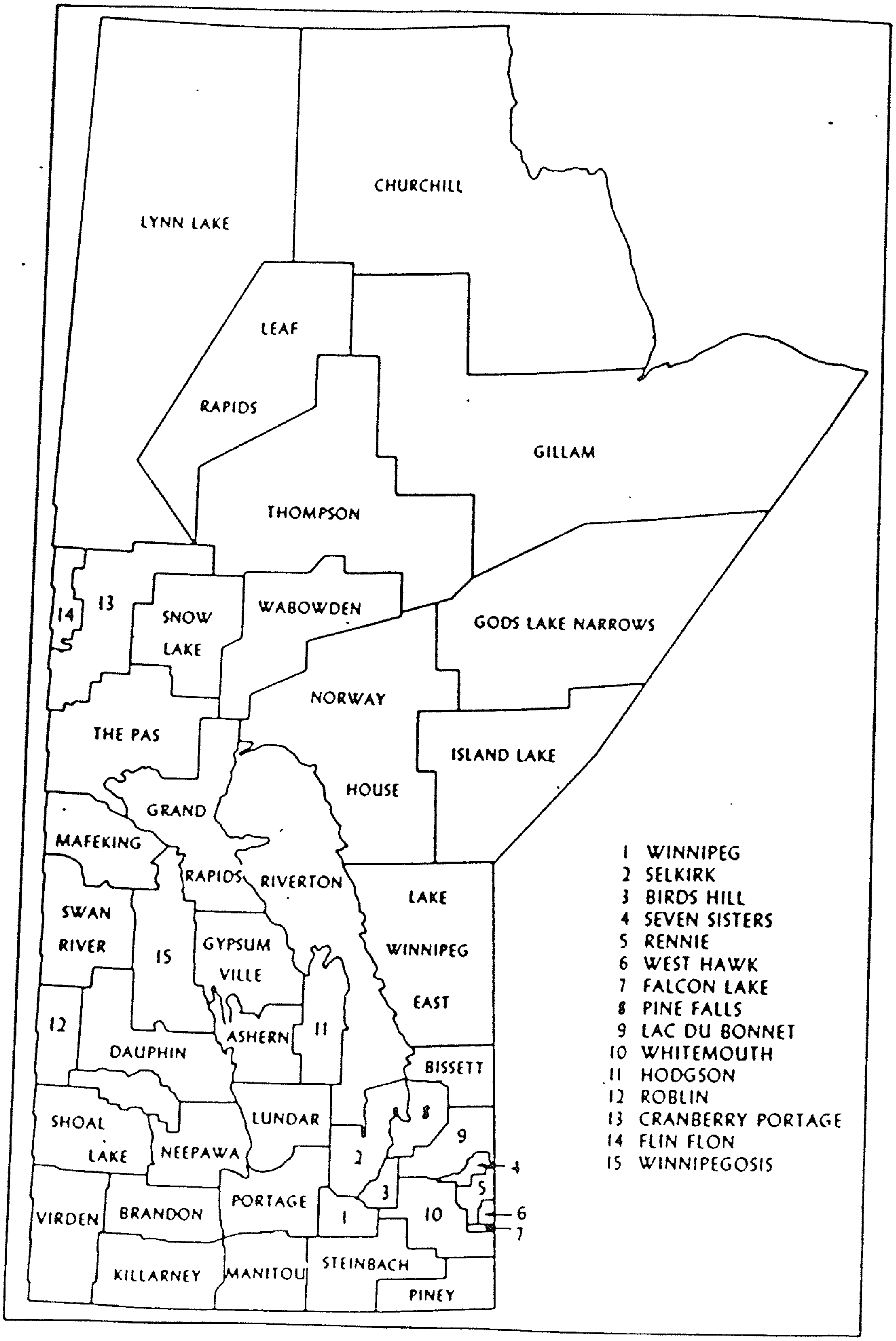


Figure 2.5: Forest Fire Management Districts.

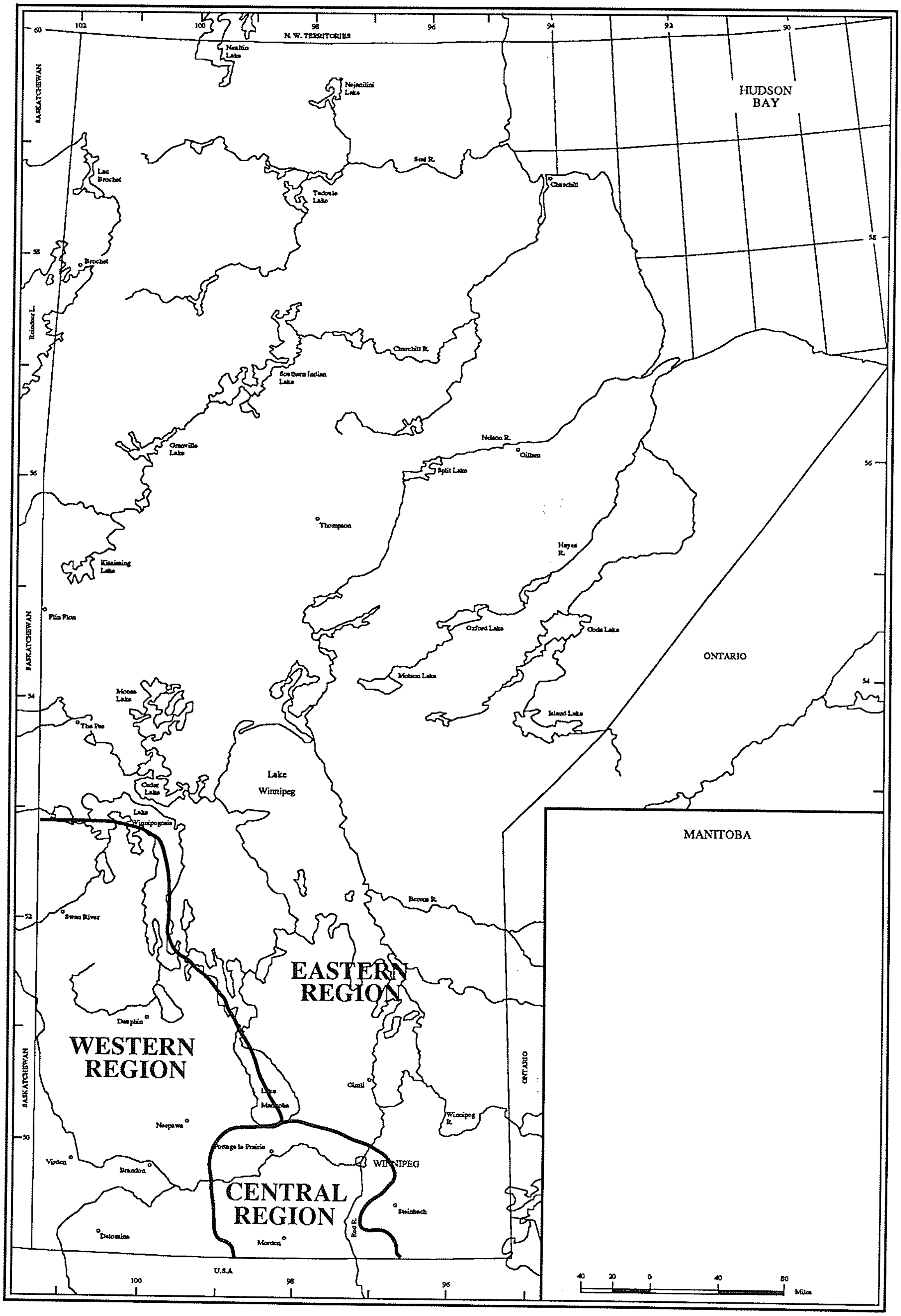


Figure 2.6: Manitoba Hydro Management Regions.

manageable districts (not shown), recording outages by date, hour, location (township, range and section number) and cause. If an interruption occurs during a thunderstorm, it is automatically classified as lightning-caused unless further investigation yields another cause.

Lightning data obtained from DF equipment provide valuable and accurate information of strike locations in spite of some shortcomings. DFs are especially useful in areas that are poorly covered or difficult to monitor by the AES. For the first time, actual locations and times of cloud-to-ground strikes can be recorded.

CHAPTER 3
DISTRIBUTION OF LIGHTNING STRIKES IN SPACE AND TIME

A network of DFs recording exact locations and times of cloud-to-ground lightning provides a much improved spatial and temporal resolution for this meso or microscale event than that provided by thunderstorm data (Reap, 1986; MacGorman et al., 1984a). A total of 67 912 valid lightning strikes were recorded by latitude and longitude and time of occurrence during the 1985 forest fire season (spanning late May to the beginning of October). These data are analyzed to show spatial and temporal patterns for the province.

Lightning flashes in Manitoba are not uniformly distributed. There are areas where maximum and minimum concentrations occur. The numbers of lightning strikes were determined for rectangular grids covering the province at two scales of 1° latitude by 1° longitude and also .5° latitude by .5° longitude. Lightning days and hours were determined for AES climate stations, then compared to thunderstorm data collected from the same weather stations. Strike density per km^2 was also calculated. Fluctuations of strike numbers diurnally for different areas was examined. A full discussion of these analyses is given in the following sections.

3.1 SPATIAL DISTRIBUTION

Strike frequencies at the two latitude/longitude grid sizes have been calculated and in both of the grid scales, three areas of the province show a high incidence of lightning occurrence with these maxima possibly indicating some influence by topography and position of large lakes (Figures 3.1 and 3.2). Areas of maximum strike frequencies for 1985 are found in:

1. West-central Manitoba near the Saskatchewan border (53° N to 56° N and approximately west of 100° W).
2. The Interlake region between Lakes Manitoba and Winnipeg.
3. Southeast Manitoba, especially east of Lake Winnipeg to the Ontario border.

North of 56° N and south of 50° N, relatively few strikes are recorded. The fewer strikes in the northern latitudes can be partially explained because of fewer thunderstorms at high latitudes. However, thunderstorm activity in the south is usually highest (LaDochy, 1985) and hence the apparent 'fewer strikes' south of 50° N appears to be an anomaly. Locations of DF sites (Figure 2.2) also contribute to the under-representation of strikes towards the north and south peripheries of the province since efficiency in recording all ground strikes and their accurate location decreases as distance increases away from DFs. Strikes are especially under-reported in the southern and eastern fringes, the eastern part of the province also having mechanical difficulties with its DF (Shipley,

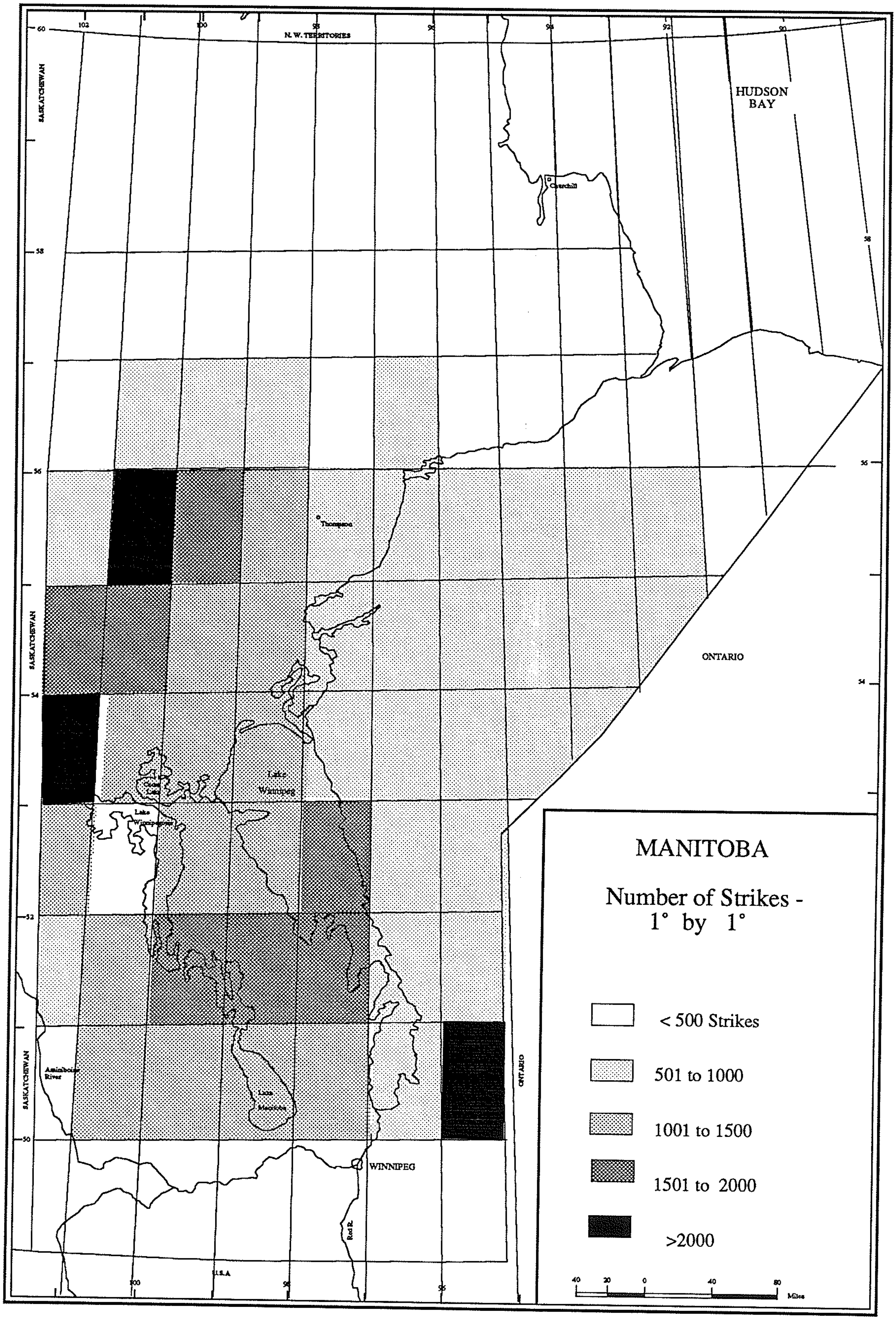


Figure 3.1: Cloud-to-Ground Strike Frequency in 1° by 1° Grids, 1985.

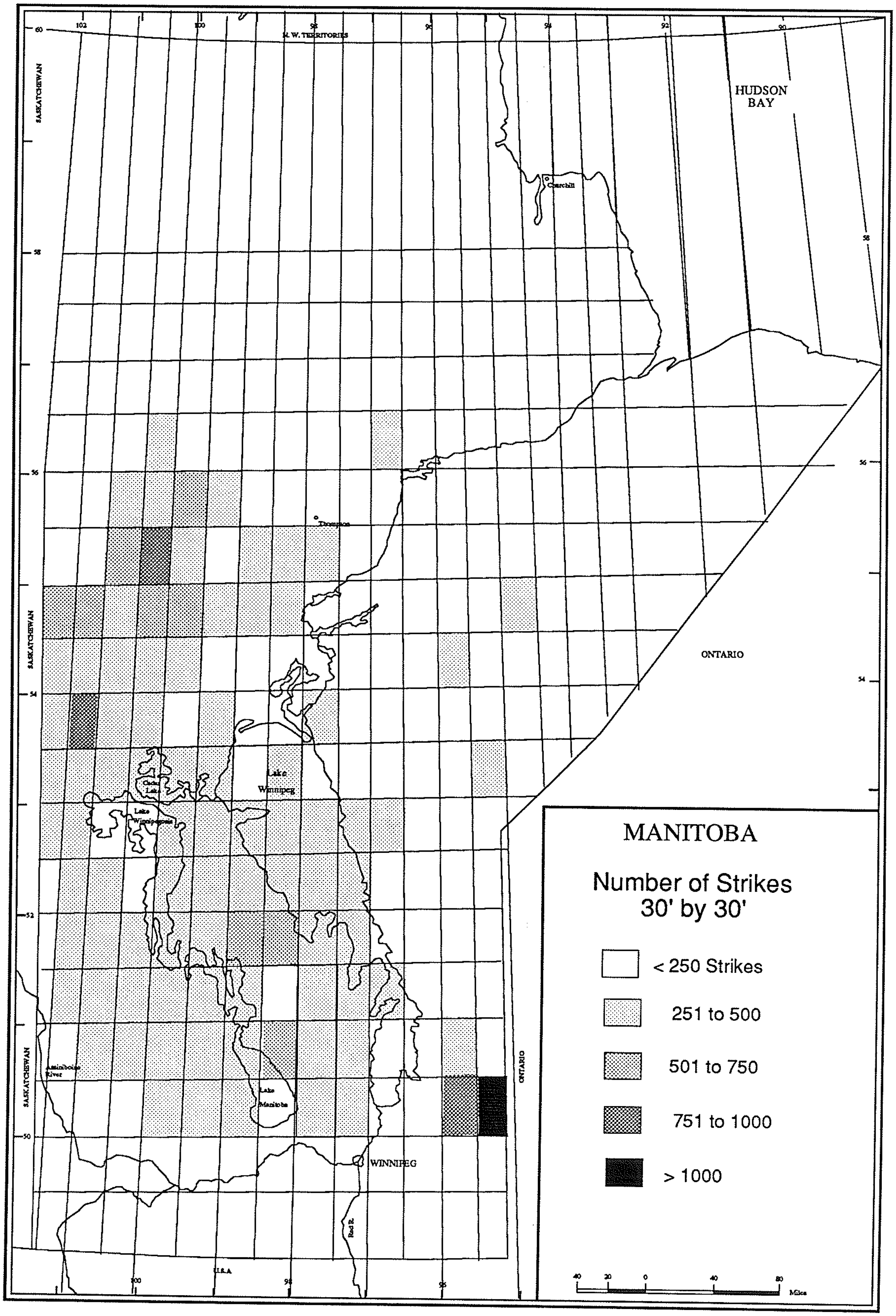


Figure 3.2: Cloud-to-Ground Strike Frequency in 30' by 30' Grids, 1985.

1988). Frequencies are also greater west of 97° W with many more active grids.

Latitudinally, the southern half of the province (50° N to 54° N) is much more active in terms of occurrences of lightning than the northern part as indicated by the fact that 65.3% of all strikes occurred south of 54° N. A band of high strike frequency is found near the southern end of the detector's range between 50° N to 50° 30' N corresponding to the southeastern maximum with a secondary maximum falling between 54° 30' N and 55° N, the central western maximum (Figure 3.3). The lowest frequencies of strikes occur north of 56° N and south of 50° N with DF data not even available for latitudes past 58° N.

Longitudinally, no significant continuous increase or decrease is visible across the province although frequencies are greater in the western part of the province (Figure 3.4). Northern Manitoba with 23 546 strikes (34.7% of the total) shows very few lightning strikes east of 98° W since thunderstorm activity is suppressed due to the cooling, stabilizing influence of Hudson Bay and the more arctic conditions inland. It follows, then, that lightning strikes are rare. A belt of moderate lightning activity is visible in the west between 99° 30' W to 101° W. Southern Manitoba shows a belt from 95° W to 96° W which is fairly active falling on the more elevated Canadian Shield. Highest frequencies of lightning occur between 97° 30' W and 99° 30' W and south of 54° N as shown on Figures 3.3 and 3.4 making visible what is termed the Interlake maximum.

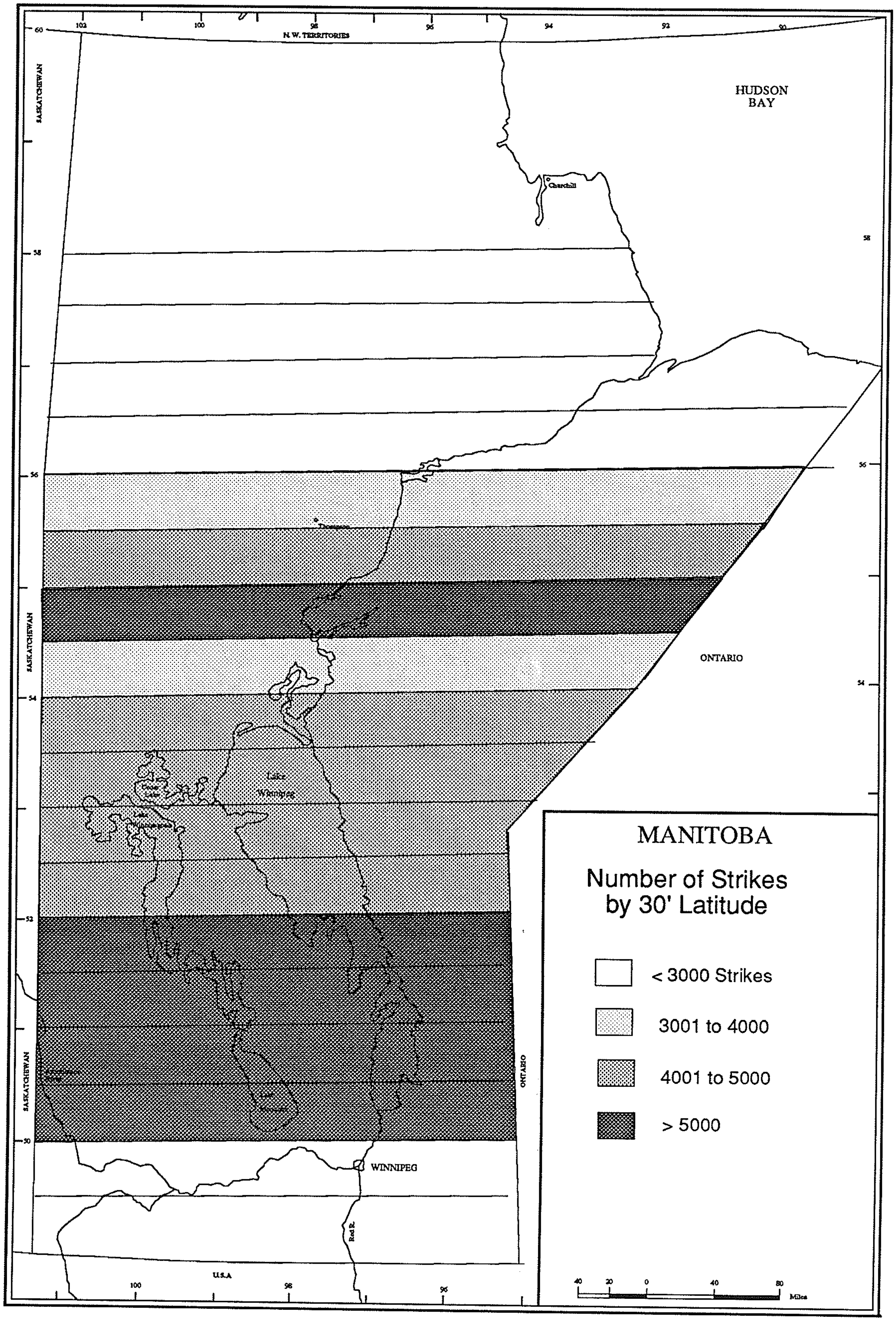


Figure 3.3: Frequency of Cloud-to-Ground Strikes by Latitude, 1985.

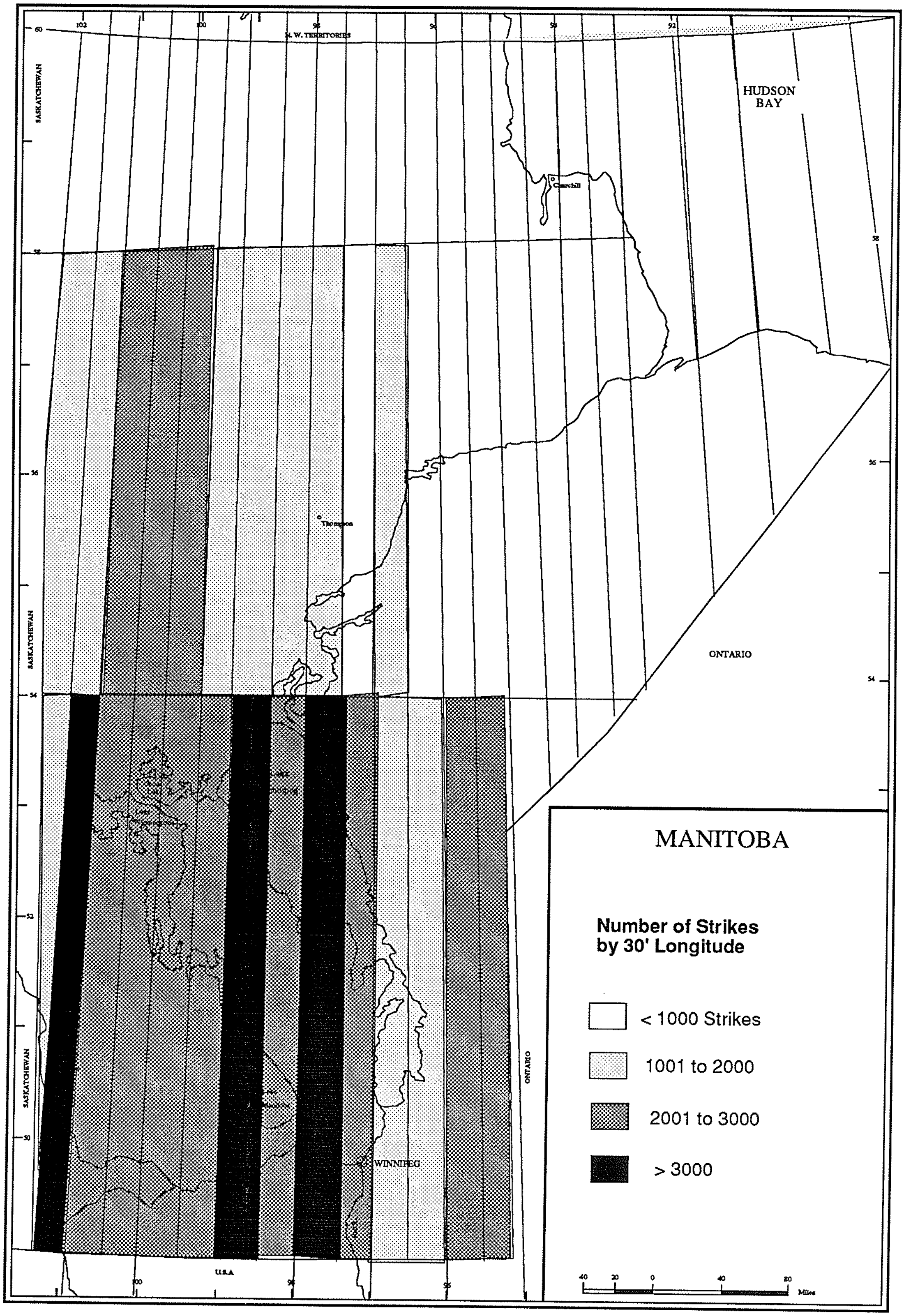


Figure 3.4: Frequency of Cloud-to-Ground Strikes by Longitude, 1985.

Like northeastern Manitoba, the Interlake area was thought to have lower thunderstorm activity due to a stabilizing effect of the lakes on the atmosphere. However, 1985 lightning strike distributions do not seem to follow this average pattern on this scale. It is possible that the lakes actually create increased instability at night when the water is mild and moisture-laden air is more buoyant. With these conditions, thunderstorm development can be enhanced, thus increasing the probability of lightning occurring. West of the Interlake area between 101° W and 101° 30' W, activity is highest where elevations are higher on the escarpment.

Lightning activity is more prevalent in the central western part of the province with high strike frequencies showing up at all levels of comparison. Thunderstorm frequencies also usually increase in the western and far southeastern parts of the province (LaDochy, 1985) which follows the notion that "in many regions of North America, increasing elevation tends to lead to increases in precipitation and thunderstorm frequencies" (Trewartha, 1980). The pattern of lightning distribution as available from DF data generally follows the pattern of 1985 thunderstorm frequencies (Figure 1.8) for the north and central portions of the province where the least number of thunderstorm days is recorded at latitudes higher than 55° N. The number of thunderstorm days increase in central Manitoba with higher thunderstorm frequencies occurring in the western, Interlake and southeastern regions. However, the southernmost part of Manitoba (49° N to 50° N) receives the most thunderstorm activity, 25 or more thunderstorms per year. This thunderstorm activity is not reflected by the lightning strike frequency distributions probably because of DF range limitations.

A more detailed comparison between 1985 lightning strike data and 1985 climate station data involves calculation of frequencies of lightning days and hours for predefined areas and is given in Sections 3.2 and 3.3.

In Figure 3.5, the province has been delineated into ten different-sized regions. Grouping the province into regions will aid in comparison of lightning characteristics in Manitoba and will help to identify the effects, if any, of topography and the large lakes on lightning distributions. Other institutions, including AES, the Fire Protection Division of Forestry and Manitoba Hydro also have the province broken down into smaller, more manageable regions. If all of these agencies could use the same system to classify regions, then direct comparisons of variables such as weather, fire incidence, power outages and lightning hits would be facilitated. Unfortunately, this is not the case since each department works with its own classification scheme. The regions created in this study are based on several sources including the AES forecast regions (Figure 3.6); the Fire Protection Division seven forest fire districts (Figure 2.5); Manitoba Hydro Service regions (Figure 2.6); and areas chosen by LaDochy (1985) that are similar in terms of thunderstorm frequencies as well as showing similarities of topography, vegetative cover and microclimate. Regions were delineated instead of using the divisions of one of the agencies in

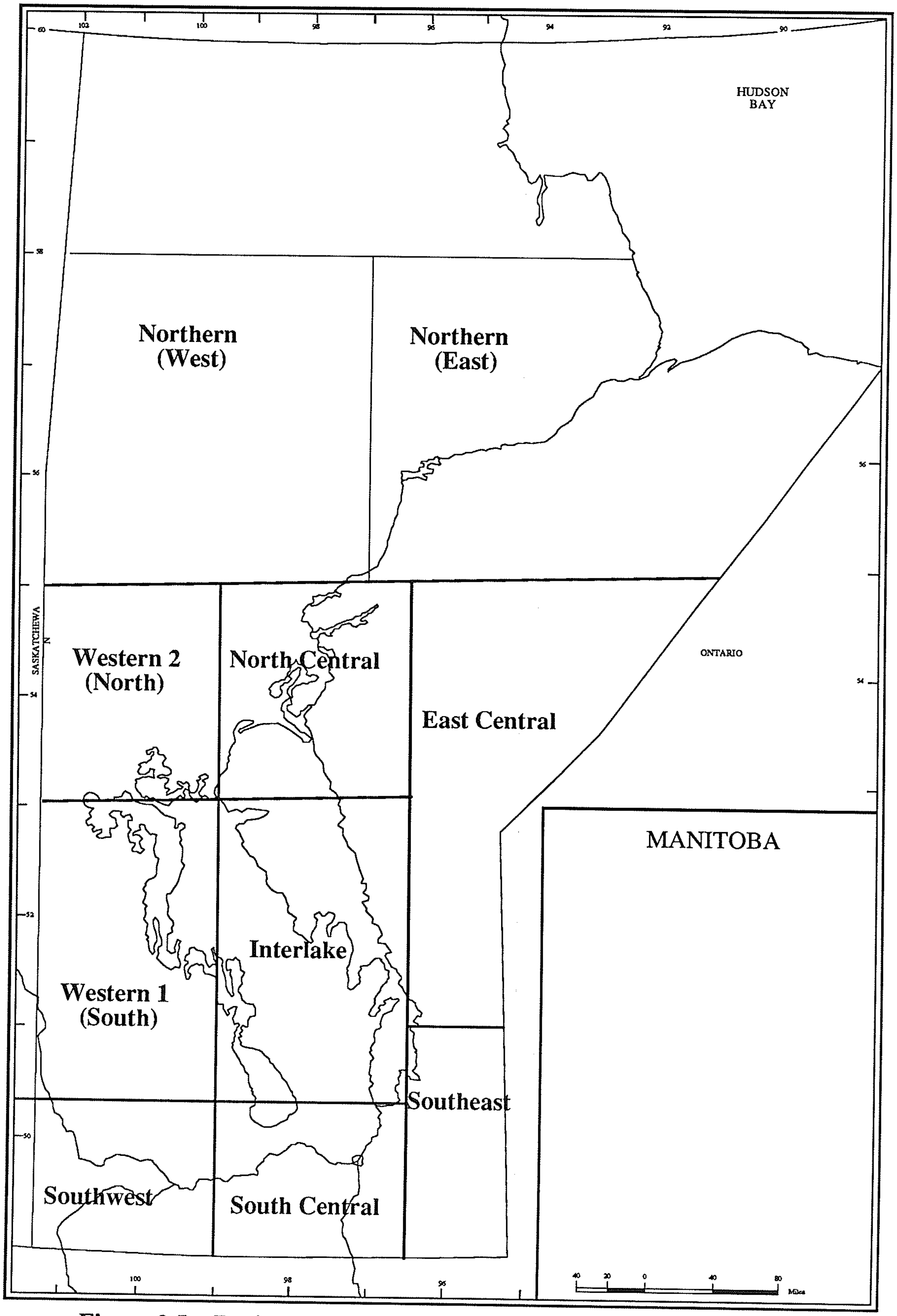


Figure 3.5: Regions used in the study.

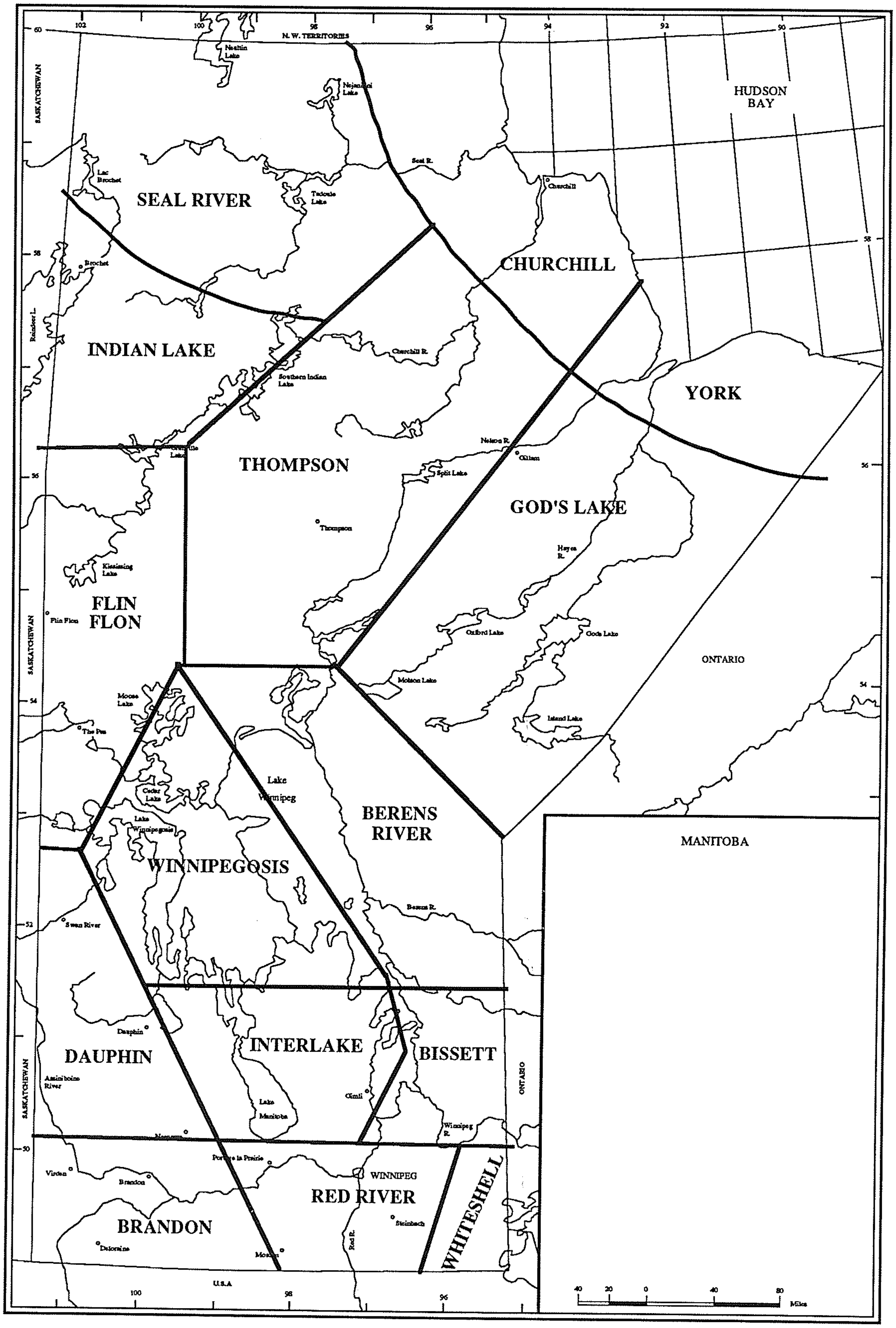


Figure 3.6: Atmospheric Environment Service Forecast Regions.

order to have more 'convenient' rectangular areas to work with. The regions created in this study are as similar as possible to the other available regions.

In order to compare the regions, lightning strike densities, number of strikes per km^2 are calculated for each region (Figure 3.7) giving a more accurate measure of lightning probability, since it equates regions of different sizes. Strike densities for the 1° by 1° grids have also been derived (Figure 3.8). The three high frequency areas identified earlier also show up in these density maps. Clearly, the Western 2 (North) region shows highest strike probabilities (.253 strikes per km^2) while the Southeast region is second highest (.238). The Interlake region does not figure as prominently with these statistics as in the analyses described previously but still has the third highest density (.203). The 1° grid cell with highest density (.382) falls in the southeast (50 to 51° N and 95 to 96° W). A value of .365 occurs at 55 to 56°N and 100 to 101°W while .319 strikes per km^2 are calculated just northwest of Lake Winnipegosis (53 to 54° N and 101 to 102° W). According to the 1° by 1° cell classification, the high density area of the Interlake records the fourth highest value. Figure 3.8 shows the variability in strike density within regions, as well as highlighting the importance of the southeast when the area south of 50° N is excluded.

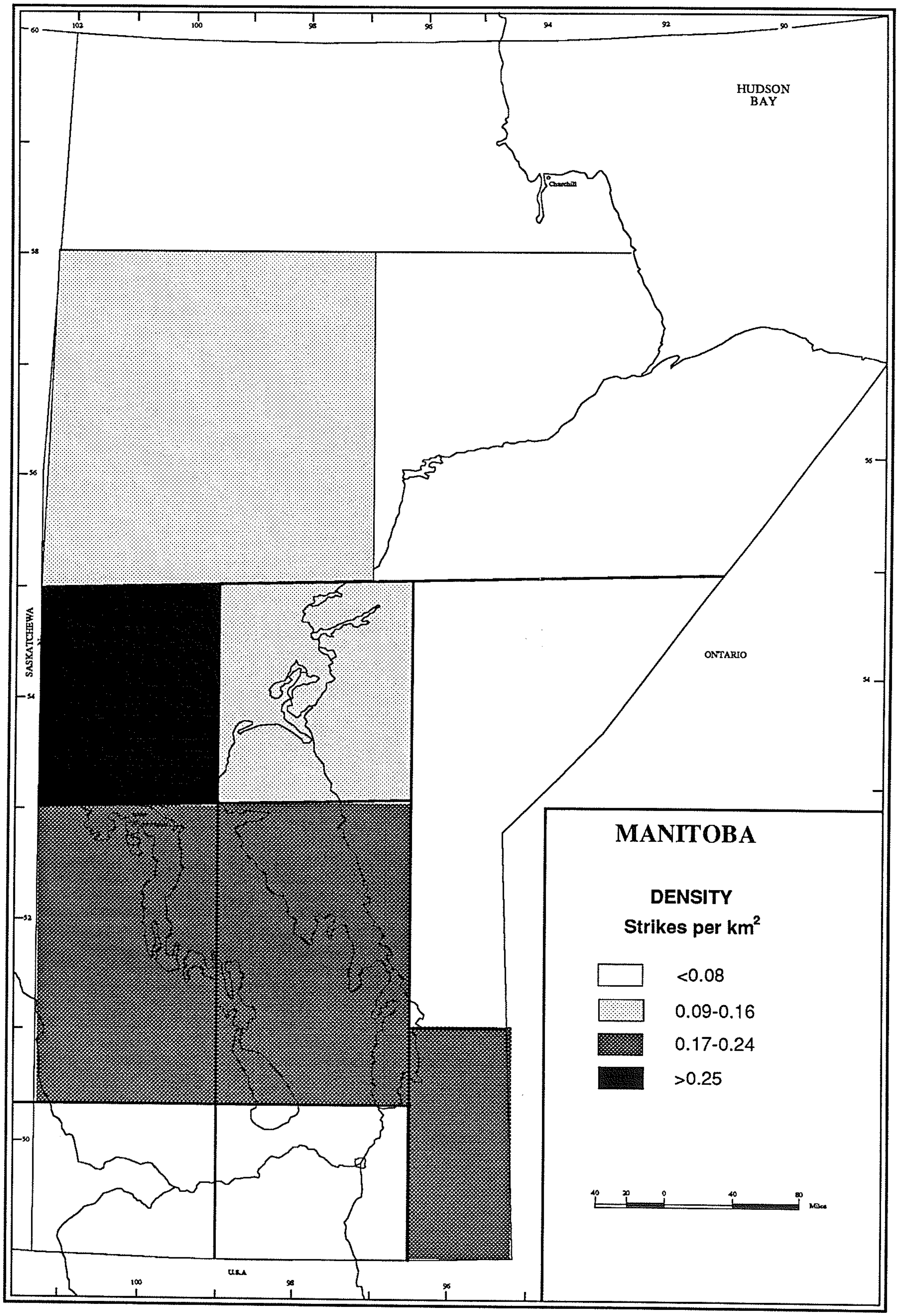


Figure 3.7: Density of Strikes by Region per km^2.

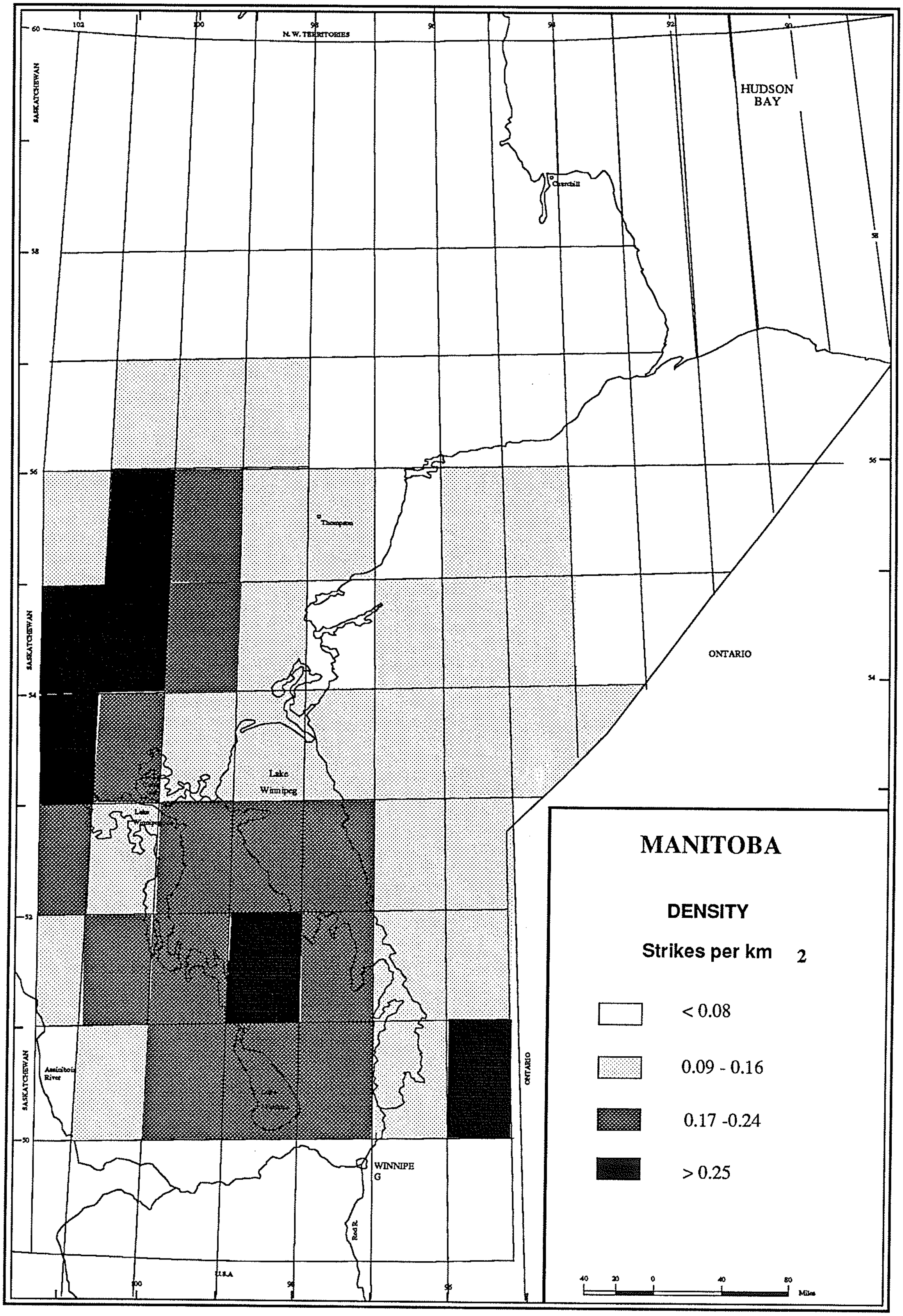


Figure 3.8: Strike Density per km^2 for 1° by 1° grids.

3.2 SEASONAL DISTRIBUTION

During the 1985 forest fire season, 67 912 cloud-to-ground lightning strikes were recorded for the entire province between 21 May and 3 October (Figure 3.9). July accounted for nearly half of the strikes with 27 260 (40.1% of the total) and August recorded 23 550 (34.7%). July normally has the highest number of thunderstorms in the province, 1985 included, along with highest frequencies of hailstorms and tornadoes, though the seasonal distribution can vary from year to year (LaDochy, 1985). Greatest number of forest fires also occur in July (LaDochy and Annett, 1983), as it did in 1985.

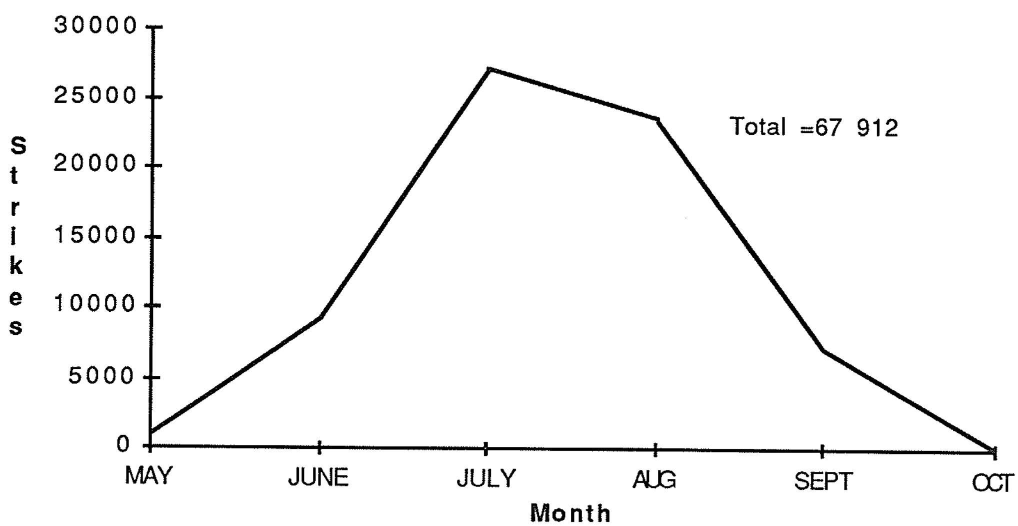


Figure 3.9: Strike Frequency for Manitoba, 1985.

The 1985 total strikes are not evenly distributed in space or time. Of the 122 days that recorded lightning, only a few very active storms account for most of the total strikes. Eleven days represented 61.8% of strikes (Table 3.1).

Storms with more than 1 500 strikes per day are chosen for detailed study. Even though 1986 is not included in other analyses due to incomplete data, in this analysis, to increase sample size, 1986 storms are included. A total of 31 storm dates have been chosen for 1985 and 1986, and of these, 13 are from July. A detailed analysis of these storms is given in Chapter 5.

For the 1985 study period of 136 days, 122 days have lightning. August leads with all 31 days recording lightning, followed by July with 28 days but with a higher total strike frequency than August. Total lightning days are compared with total thunderstorm days for the province (represented by 11 climate stations) (Figure 3.10). Both thunderstorm and lightning days increase from May, and while thunderstorm days reach their maximum in July, lightning days are maximized in August. Throughout the season, more lightning days are recorded than thunderstorm days, this discrepancy arises because of the greater spatial coverage by DFs detecting lightning strikes (thunderstorms) in remote areas not monitored by the relatively few weather stations. To be considered a lightning day, a day must have received at least one strike while a thunderstorm day is defined as a day in which thunder is heard (Section 1.3). All stations experienced

	Date		Frequency of Strikes	
1985	June	20-21	3 422	
	July	2-3	10 545	
		12	2 701	
		15	2 475	
		23	4 061	
		27	1 782	
	Aug	3	2 061	
		5	7 091	
		26	3 701	
		31	2 567	
	Sept	5	1 569	
		TOTAL	41 975	(61.8%)
1986	June	11	7 281	
		19	N/A	
		21	1 988	
		24	3 889	
		25	14 364	
	July	3	5 159	
		5	4 040	
		17	4 186	
		22	3 183	
		23	6 214	
		25	6 808	
		28	6 315	
		29	12 971	
	Aug	3	8 806	
		6	6 779	
		7	2 842	
		8	2 119	
		13	4 257	
		14	3 223	
		19	7 919	
		TOTAL	109 120	(71.1%)

Table 3.1: Days With More Than 1 500 Lightning Strikes, 1985 and 1986.

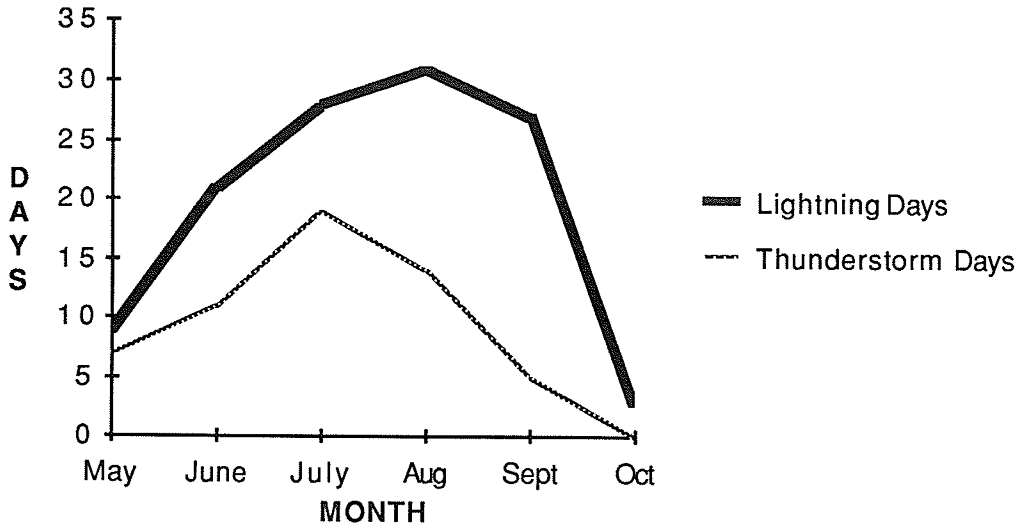
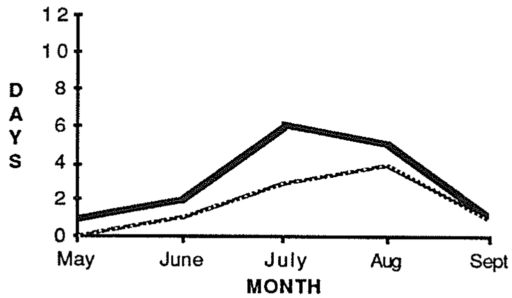


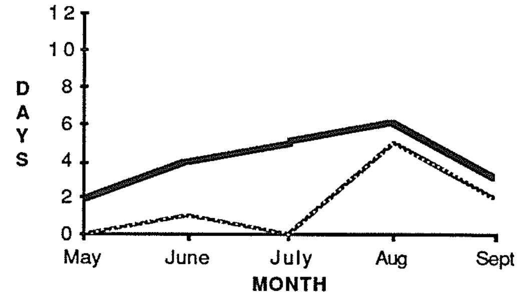
Figure 3.10: Thunderstorm Days and Lightning Days for Manitoba, 1985.

fewer than average thunderstorm days in 1985. Since only 11 sample stations are used to determine thunderstorm days for the entire province and a lightning day is any day anywhere in the province that recorded a strike, some thunderstorms have probably not been included because a selected few climatic stations represent such a large area. On the other hand, a climate station could hear thunder on a day when only within-cloud lightning occurred, or a DF located the strike just beyond the audible thunderstorm range of a station. Lightning days are also calculated for grids around each of 11 climatic stations, then compared with thunderstorm days for each station (Figures 3.11a to k). Each station grid covers approximately a .2° square area around each station. This size area is chosen because it is approximately the distance that thunder would be heard by AES observers. For seven

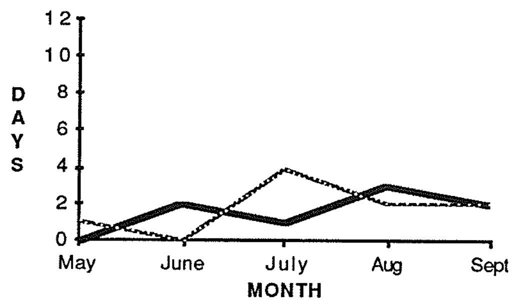
Figure 3.11: Thunderstorm Days and Lightning Days at Climate Stations, 1985.



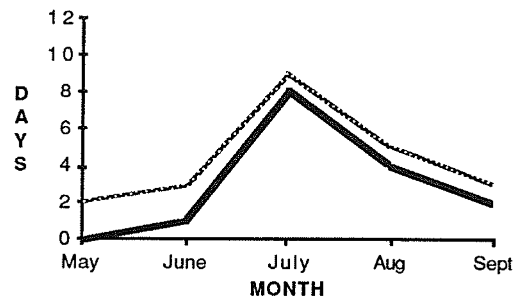
a: Brandon



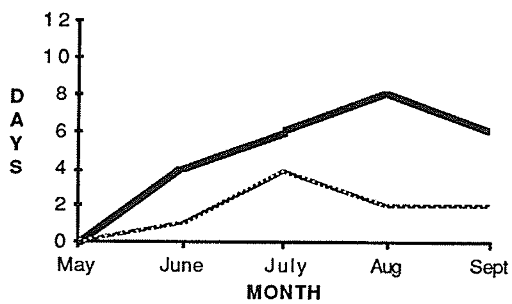
b: Dauphin



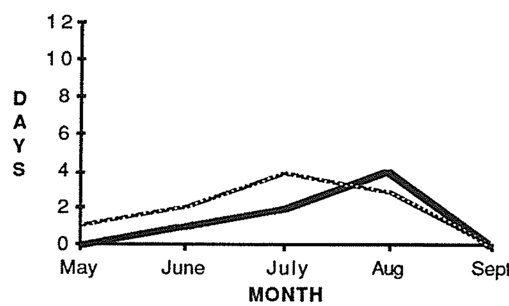
c: Gillam



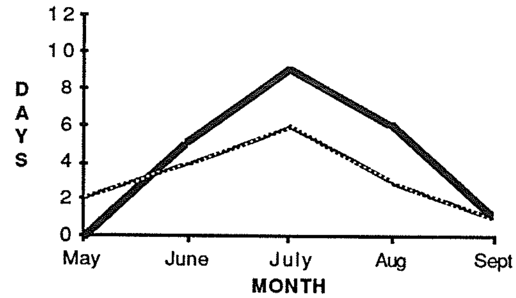
d: Gimli



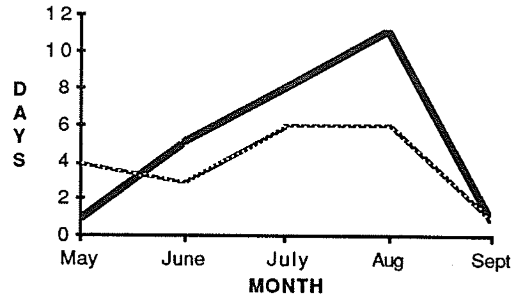
e: Island Lake



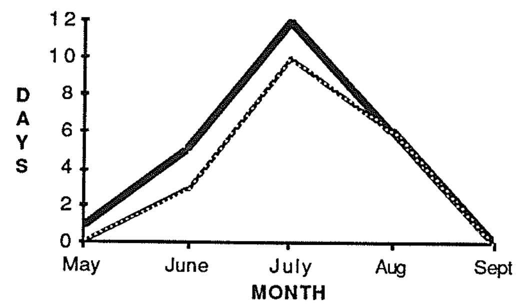
f: Lynn Lake



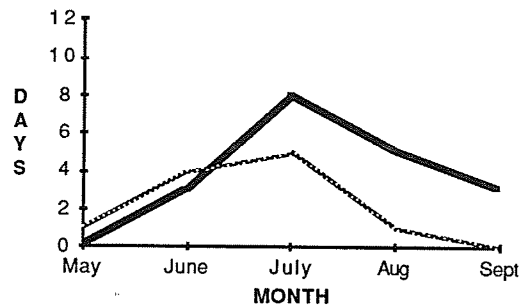
g: Norway House



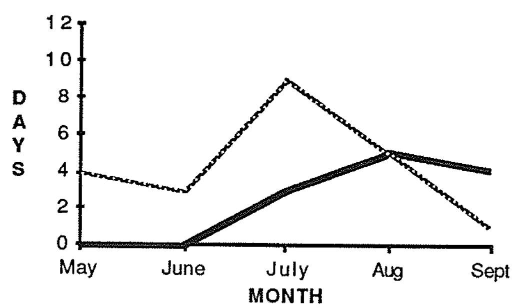
h: Portage la Prairie



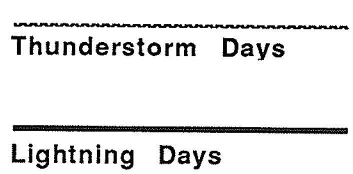
i: The Pas



j: Thompson



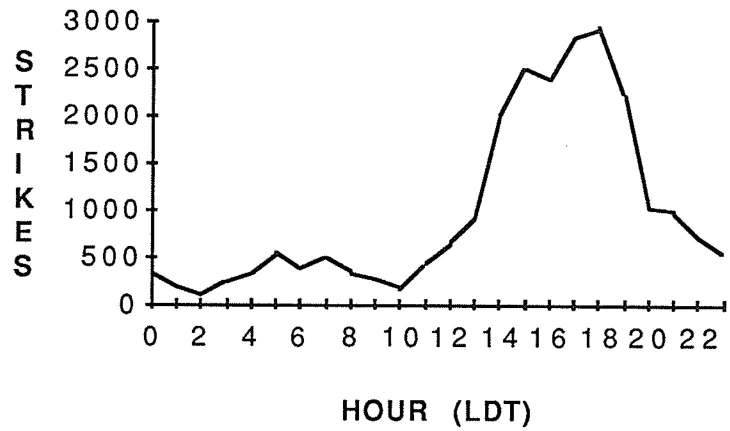
k: Winnipeg



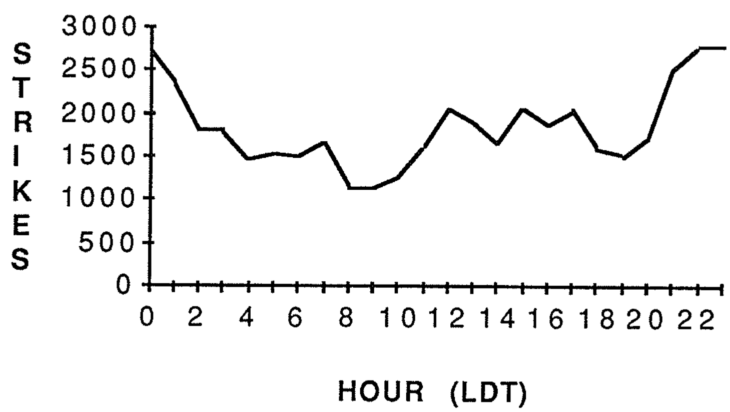
of 11 stations (Brandon, Dauphin, Island Lake, Norway House, Portage la Prairie, The Pas and Thompson), lightning days are greater than thunderstorm days. Gimli, Lynn Lake and Winnipeg generally have fewer lightning days than thunderstorm days. This lower representation of lightning days for the two southeastern stations can be attributed to poor coverage by DFs in this area. A greater representation of lightning days tends to occur for the stations located within DFs optimum ranges. Lynn Lake, because of its northerly location is also at the limits of a DF's range, possibly having an incomplete record. Gillam station records two months with higher thunderstorm days and two months with higher lightning days thus making it difficult to provide any classification for that station. Since DF data is not available for latitudes past 58° N, the Churchill station could not be included in the comparison.

3.3 DIURNAL DISTRIBUTION

Lightning strikes, like many other meteorological variables fluctuate with the time of day. Figure 3.12 shows the hourly progression of lightning frequencies for northern and southern Manitoba for 1985. The north records very few lightning strikes in the morning hours, almost all of the activity being concentrated in the afternoon and early evening. Maximum number of strikes occurred between 1500 and 1900 LDT, minimum between midnight and 1200 LDT. In the south, maximum activity occurs from 2100 to 0100 LDT with a secondary peak in the afternoon. High lightning activity levels later at night follow the typical pattern of higher



a: Northern Manitoba.



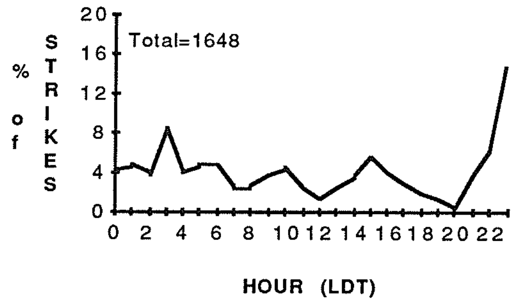
b: Southern Manitoba.

Figure 3.12: Hourly Distribution of Strikes for Manitoba, 1985.

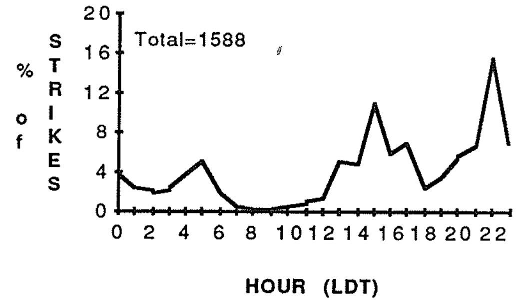
frequency of nocturnal thunderstorms of the northern plains states (Wallace, 1975) and the same thunderstorm pattern has been found for Manitoba by LaDochy (1985). The primary peak in late afternoon-early evening is similar to the more dominant peak found by Lopez and Holle (1986) for northeast Colorado lightning and slightly later than for central Florida. A morning minimum extends from 0200 to 1200 LDT.

The diurnal pattern also varies in the previously defined regions. In the south and west parts of the province, a late night (before midnight) peak dominates (Figures 3.13a, b, c and d), the southwest also showing high afternoon frequencies. A late night peak is joined by an early a.m. peak in the Interlake and North Central regions of Manitoba (Figures 3.13e and f). The Southeast region (Figure 3.13g) has mid-day and late night peaks, the only region with this pattern. Farther north, the East Central region shows both the mid-day and late night peaks along with an early evening active period (Figure 3.13h). Northern Manitoba (Figures 3.13i and j) show a pronounced greater concentration of late afternoon strikes (more than 50% of strikes) with significantly lower values at other times.

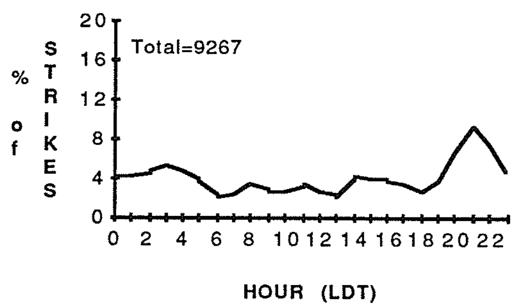
Various patterns of lightning activity are visible throughout the day for areas north and south of 54° N (Figure 3.14). To the north, lightning is infrequent at night and before late morning (2000 to 1159 LDT). Some activity becomes visible in late morning in the west (higher elevation) (Figure 3.14d). Frequency continues to remain high in the west, in the afternoon (Figure 3.14e). The



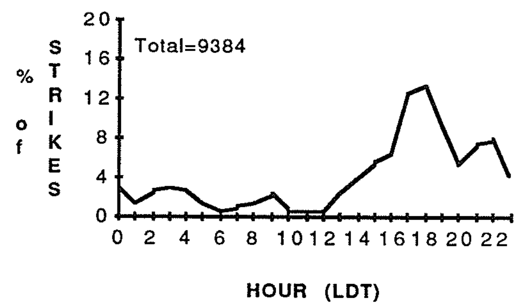
a: South Central Region



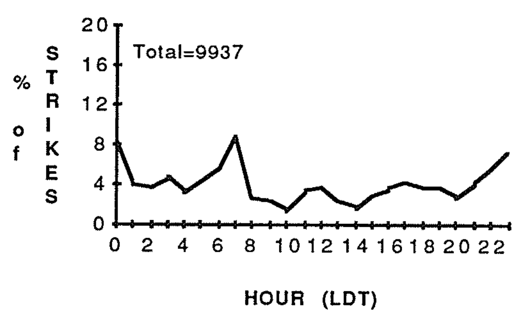
b: Southwest Region



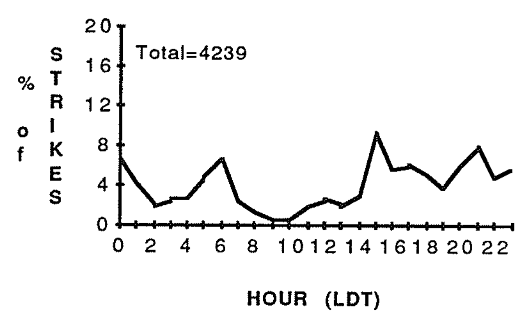
c: West1 (South) Region



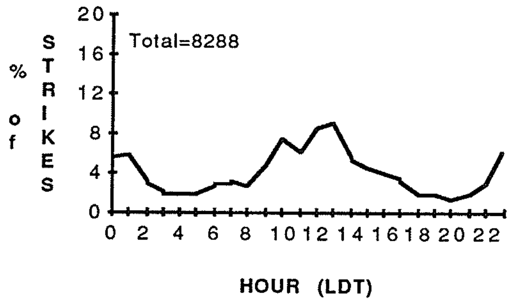
d: West2 (North) Region



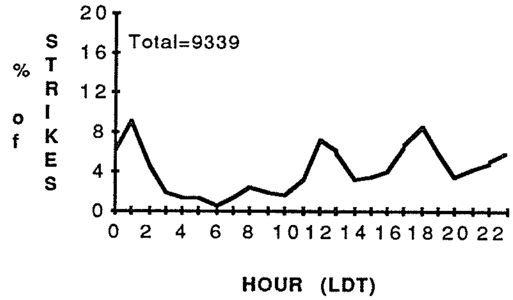
e: Interlake Region



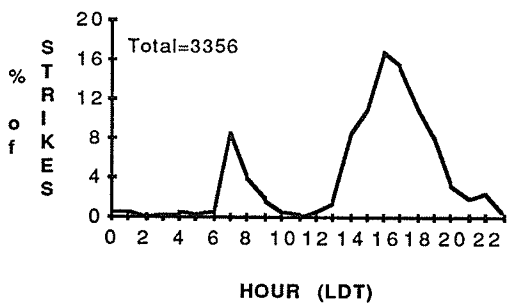
f: North Central Region



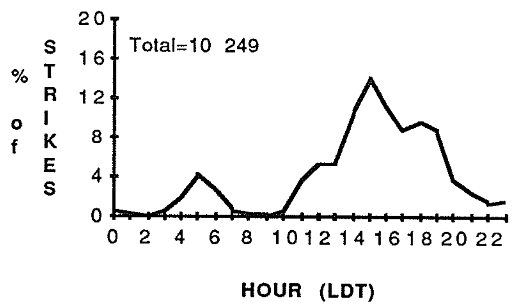
g: Southeast Region



h: East Central Region

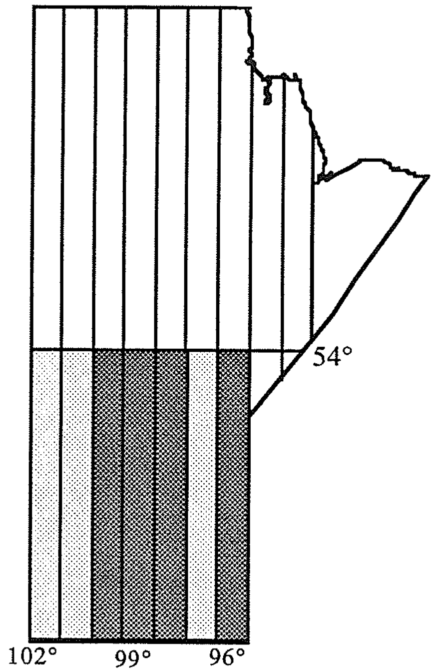


i: Northern (East) Region

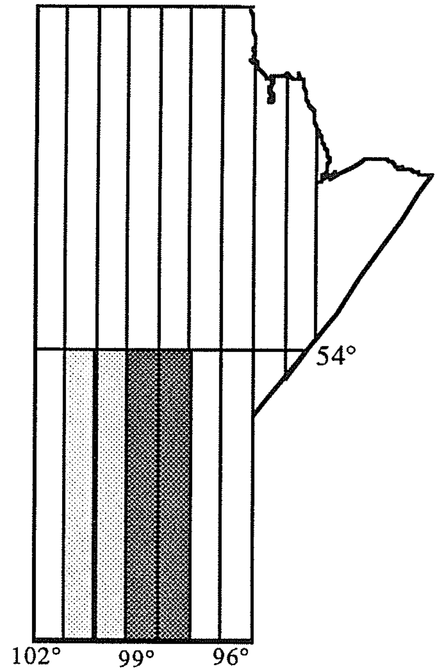


j: Northern (West) Region

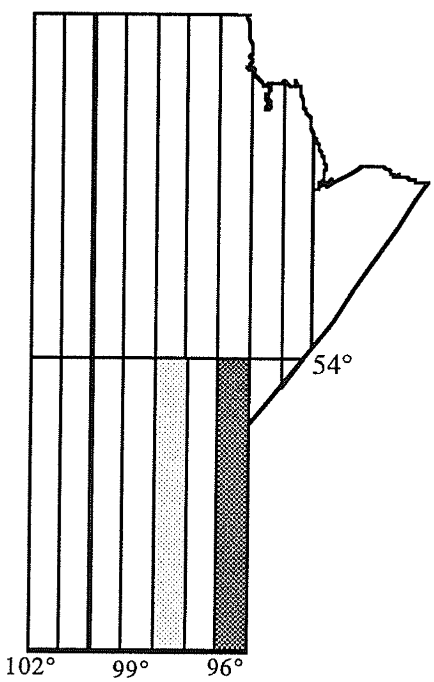
Figure 3.13: Hourly Distribution of Lightning Strikes for Regions, 1985.



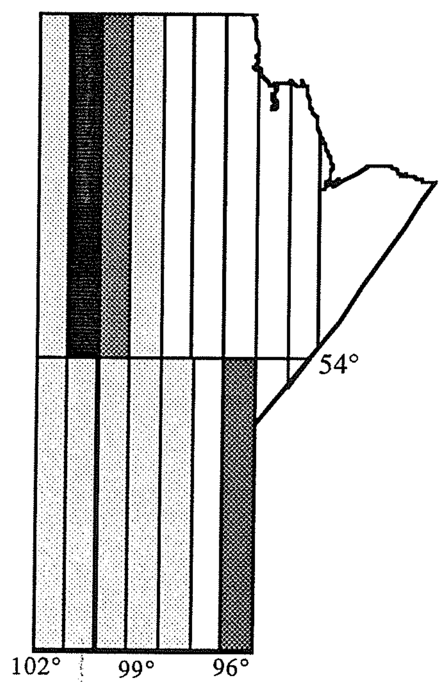
a) **0000-0359**



b) **0400-0759**



c) **0800-1159**



d) **1200-1559**

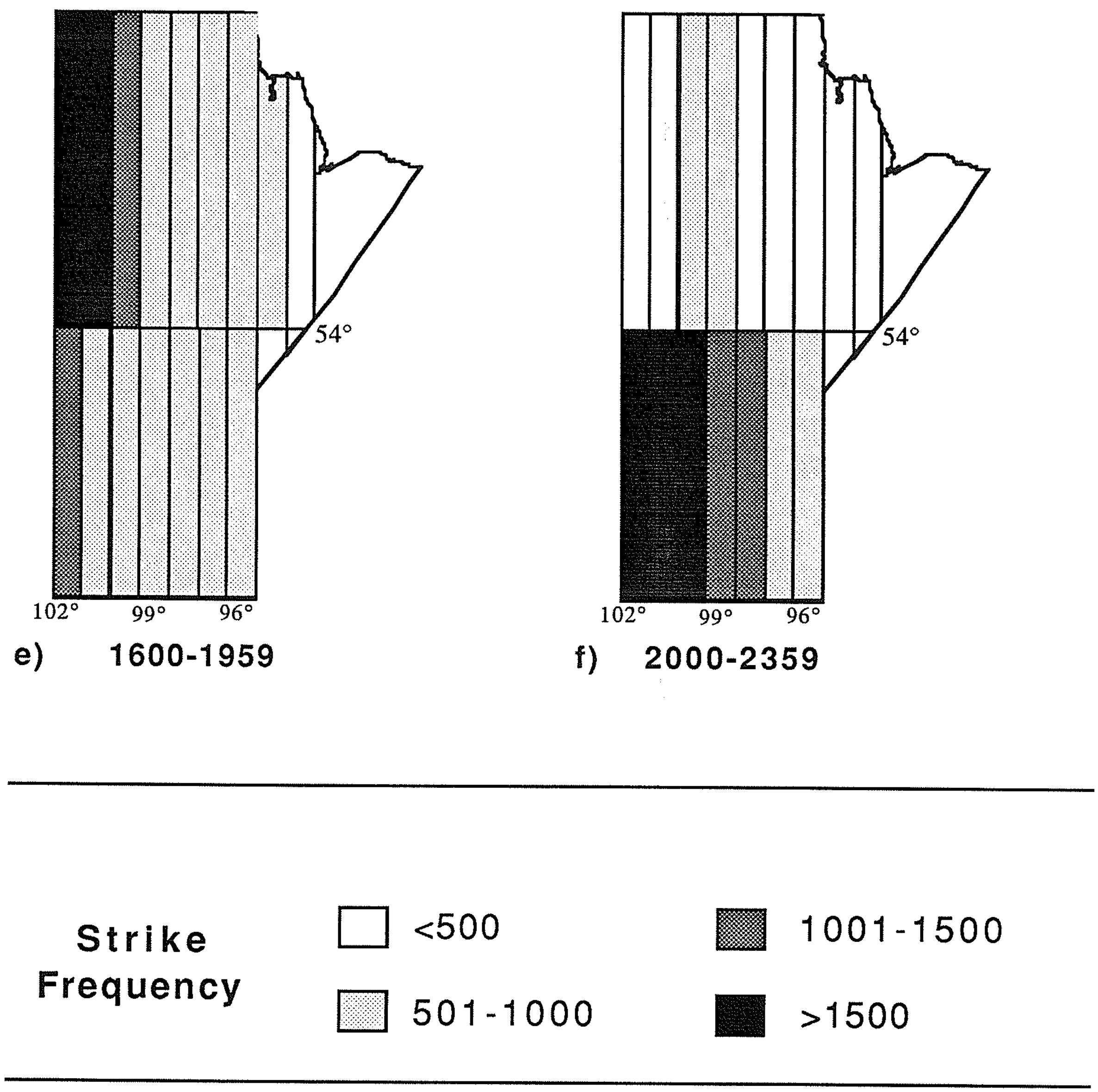


Figure 3.14: Number of Lightning Strikes per Band of Longitude by Time (North and South of 54°N).

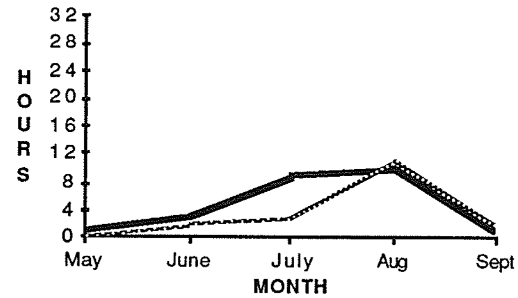
activity spreads eastward as the day progresses, but the highest frequencies are noticeable west of 99° 30' W for the early afternoon. Strike frequency falls quite drastically over almost all of northern Manitoba after this afternoon height of activity.

The south, having a greater overall frequency of strikes, tends to remain more active during all time periods. To the south, late morning lightning is recorded in the east over the elevated Shield area (Figure 3.14c). By afternoon, the higher western and eastern portions have greater strike frequencies, with numbers decreasing in the east by early evening but remaining high in the west (Figures 3.14d, e and f). Almost all of southern Manitoba reaches peak levels at night (2000 to midnight LDT). After midnight (LDT), lightning activity decreases in the west but the central plains region continues to have high lightning frequencies (Figures 3.14a and b), high frequencies shifting further east by mid-morning.

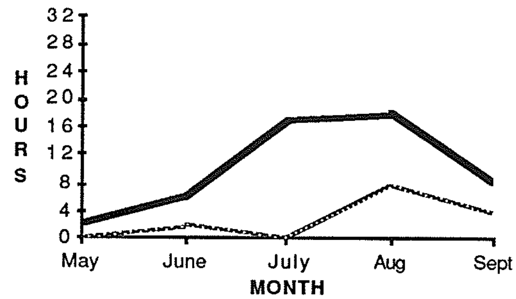
This progression of lightning (thunderstorm) activity eastward (in all of Manitoba), first in the afternoon and later in the early morning was also seen east of the Rockies in Alberta and Colorado (Summer and Paul, 1970). It is noticeable that the southern part of the province is more active later into the night while the northern part receives most lightning activity earlier, following the diurnal pattern of thunderstorm occurrence as described by LaDochy (1985).

For each climate station, thunderstorm hours defined as any hour during which thunder is heard (AES) have been compared with lightning hours for the grid surrounding each station (Figures 3.15a to k). A lightning hour is recorded if at least one cloud-to-ground

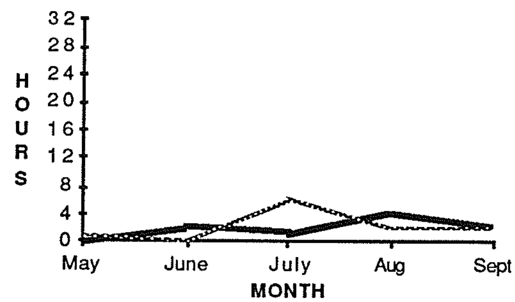
Figure 3.15: Thunderstorm Hours and Lightning Hours at Climate Stations, 1985



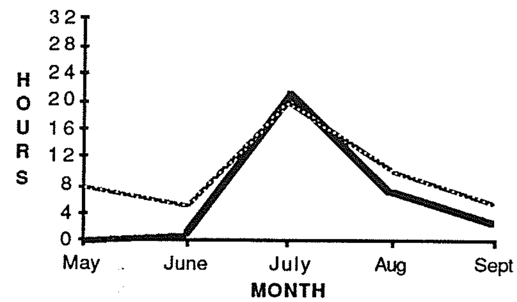
a: Brandon



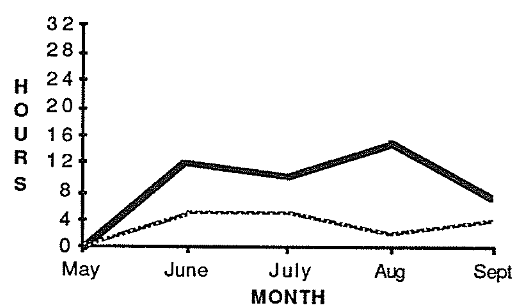
b: Dauphin



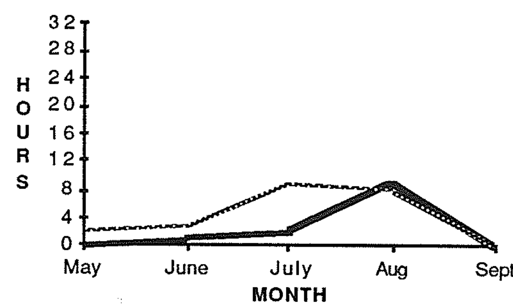
c: Gillam



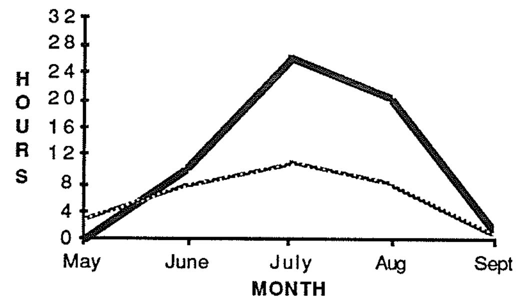
d: Gimli



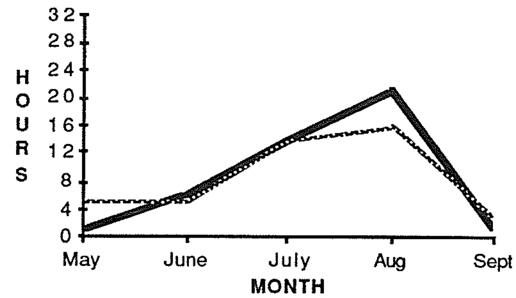
e: Island Lake



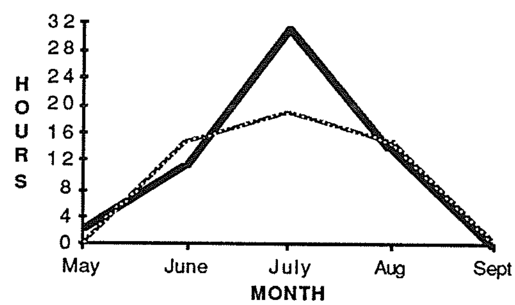
f: Lynn Lake



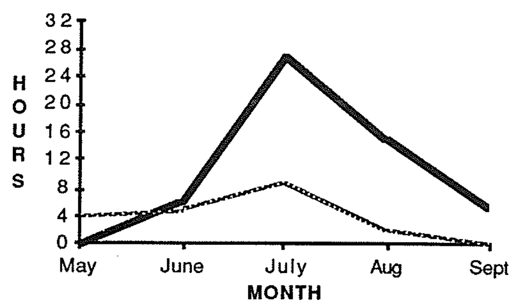
g: Norway House



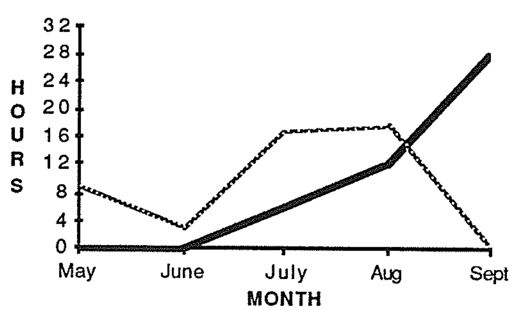
h: Portage la Prairie



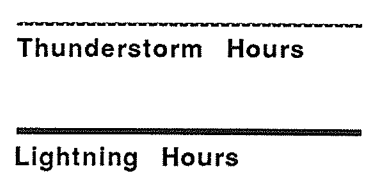
i: The Pas



j: Thompson



k: Winnipeg



strike occurs during any hour within .2° (about 10 km) of a station. Stations that report more lightning than thunderstorm hours include Brandon, Dauphin, Island Lake, Norway House, Portage la Prairie, The Pas and Thompson. All of these stations also recorded more lightning than thunderstorm days in Section 3.2. Gillam, Gimli, Lynn Lake and Winnipeg generally record fewer lightning than thunderstorm hours. Both The Pas and Winnipeg, though generally having fewer lightning than thunderstorm hours, show one month (July for the Pas and September for Winnipeg) with lightning hours significantly greater than thunderstorm hours. Again, Churchill is not within the DF range, thereby excluding this station from classification.

3.4 AGREEMENT BETWEEN THUNDERSTORM AND LIGHTNING DAYS AND HOURS

For each station, thunderstorm day and hour data are compared with lightning day and hour data using a Binomial Probability Distribution. This statistic indicated whether the concurrence of thunderstorm and lightning days can be attributed to chance. What is the probability of the number of 'agreements' between thunderstorm and lightning days (or hours) occurring by chance, given a population of 133 days (3082 hours) and a random sample of the thunderstorm days (hours)?

Every station except Winnipeg has an agreement between thunderstorm and lightning days that gives 99% confidence the concurrence is not by chance (Table 3.2). Gimli has the most significant concurrence (99.99999%) and Winnipeg the lowest (95%). Even with the high confidence levels, detector data still recorded lightning days in which thunderstorm data do not show and thunderstorm data recorded thunderstorm days which detector data do not indicate. If all the days that are included in both sets of data are used to represent total thunderstorm/lightning days, it is found that the two measures agree on day on average of 32.9% of the time (Table 3.3). Gimli again shows the greatest agreement (54.2%) and Winnipeg the lowest (14.3%). Differences in confidence levels and agreements can be attributed to several factors. First, a thunderstorm (lightning) day can be missed if a station is not within optimum range of a DF, triangulation of location cannot be accomplished or other instrumental error occurs. Second, it is also possible for no cloud-to-ground lightning to fall within the defined limits of a station. Thunderstorm days are recorded if thunder is audible or lightning seen when it is too noisy for thunder to be heard but lightning is not necessarily only cloud-to-ground. Third, a thunderstorm can also be missed by a weather observing station. In a large city like Winnipeg, a storm in one part of the city may not be known about in another. In the remote areas, weather observation may not be very accurate due to manpower limitations in these areas.

Station	Probability
Brandon	.000006577
Dauphin	.003281896
Gillam	.000714962
Gimli	.000000016
Island Lake	000008293
Lynn Lake	.000077665
Norway House	.000122479
Portage la Prairie	.007320613
The Pas	.000014916
Thompson	.000449624
Winnipeg	.053965670

Table 3.2: Probabilities that the Number of Agreements between Thunderstorm and Lightning Days are Occurring by Chance.

Brandon	38.9%	7	agree of	18
Dauphin	20.8%	5	agree of	24
Gillam	38.8%	4	agree of	13
Gimli	54.2%	13	agree of	24
Island Lake	32.0%	8	agree of	25
Lynn Lake	38.5%	5	agree of	13
Norway House	37.0%	10	agree of	27
Portage	21.1%	8	agree of	38
The Pas	40.0%	12	agree of	30
Thompson	26.1%	6	agree of	23
Winnipeg	14.3%	4	agree of	28

Table 3.3: Agreement of Thunderstorm Days and Lightning Days for climate stations, 1985.

Station	Probability
Brandon	.000000001
Dauphin	.000000019
Gillam	.992192000
Gimli	.000000001
Island Lake	.000000001
Lynn Lake	.000000019
Norway House	.000000001
Portage la Prairie	.000002269
The Pas	.000000001
Thompson	.000000001
Winnipeg	.000000006

Table 3.4: Probabilities that the Number of Agreements between Thunderstorm and Lightning Hours are Occurring by Chance.

Hours in which thunderstorms and lightning occur simultaneously are compared using days with corresponding thunderstorm and lightning days. The chance of the same thunderstorm and lightning hours occurring are calculated. High probabilities (greater than 99.9%) are found for all stations but Gillam (Table 3.4) that the agreement did not occur by chance. Gillam did not have any thunderstorm or lightning hours in common.

It was expected that the thunderstorm and lightning data where all days of data were included would be more similar. However, if it is assumed that lightning data are fairly accurate, then perhaps these findings are pointing out some shortcomings of current thunderstorm data. On the other hand, some shortcomings of DF data may also be responsible for discrepancies. It is encouraging, however, to see that the days (hours) which stations do have in common show such high probabilities that this association is not a chance occurrence. But, it is odd that there are so many days (hours) that are different between the two sources.

Perhaps both sources should be used in more comparative studies in order to decide if current thunderstorm recording methods are as accurate as they could be, especially in more remote regions. Lightning data could be used to supplement (possibly improve) standard recording methods. In order to get the most complete and accurate statistics on thunderstorms and lightning, it is important to take into account any available information about the phenomena. Integration of standard meteorological thunderstorm recording techniques and the lightning DF data could eventually provide an improved thunderstorm (lightning) climatology for the province.

CHAPTER 4

FOREST FIRES AND POWER INTERRUPTIONS

4.1 FOREST FIRES

Records of lightning-caused forest fires have been used previously to construct a damage-based lightning climatology for Manitoba (LaDochy and Annett, 1983). Close to half of all forest fires in this province are usually caused by lightning. In 1985 and 1986, 37.1% of fires were lightning-caused. There can, of course be considerable variability from year to year in the number of fires and area burned, as was the case with 1985 and 1986. In 1985, total forest fires numbered 346 (less than the average of 450 a year) with 136 (39.3%) being lightning-ignited, while in 1986, 217 fires were recorded, 73 (33.6%) being attributed to lightning. Similarly, more than 98 500 hectares (Ha) were burned in 1985 (greater than the average of 70 000 Ha in a year) but around 38 200 Ha were destroyed during the 1986 season. Areas burned by individual fires ranged from one to 39 770 square hectares, 1985 recording the largest fire. The greatest area burned in 1986 was 28 811 hectares. The size of the area ravaged by a particular fire depends upon numerous variables, moisture conditions, fuel availability and wind speed and direction, for example. Since 1985 as a whole was drier than 1986, this moisture difference is probably the single greatest factor explaining the discrepancy in number of fires for the two years. Precipitation levels at both Thompson and Winnipeg (representing the northern and southern parts of Manitoba), were much below normal in winter and spring (1984-85). In the south, dryness continued throughout the 1985 summer except in August (Figure 4.1a). With dry ground, the probability of lightning igniting a fire is greatly increased. In the next year (Figure 4.1b), precipitation levels for winter fluctuated more, though still falling below normal on several months. However, a wet spring and adequate rainfall in the summer, especially in the north, reduced forest fire hazard by dampening ground fuel, thus making probabilities of ignition by lightning less likely.

Any lightning-caused fire is not necessarily visible at the actual time of ignition because an observer may not spot it or a situation exists such that visible indications of fire were temporarily suppressed. Time of fire ignition as recorded by the Provincial Forest Service then may not always exactly coincide with storm activity in the area. With lightning detection equipment, it is now easier to pin-point the strike(s) which caused a fire and know the exact time of ignition.

4.1.1 SPATIAL DISTRIBUTION OF LIGHTNING-CAUSED FOREST FIRES

The incidence of lightning-caused forest fires during 1985 and 1986 was greatest in the Fire Management's northeastern region of the province (Figure 2.5) (103 fires total) with the eastern region recording the second highest number of fires (66). While in 1986

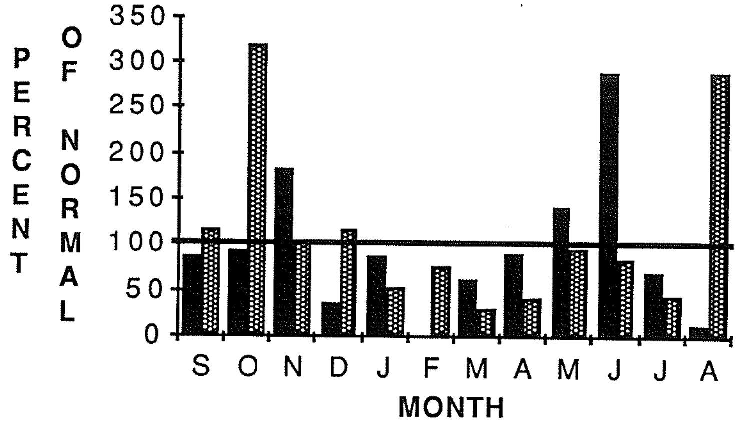


Figure 4.1a: Precipitation at Thompson and Winnipeg, 1984-5 (100%=Normal).

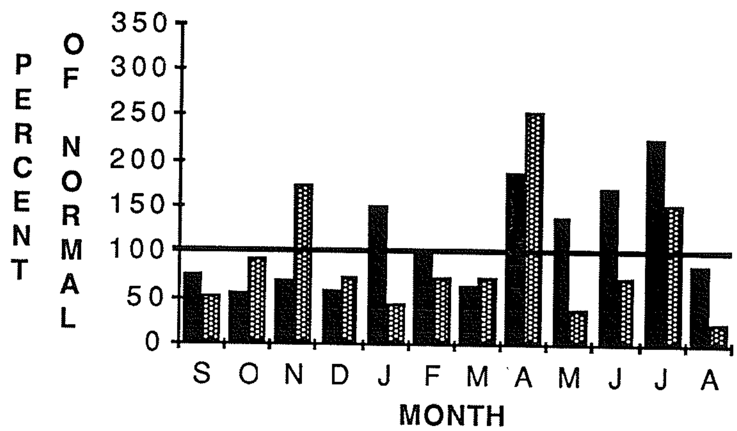


Figure 4.1b: Precipitation at Thompson and Winnipeg, 1985-6 (100%=Normal).

the Northeast region experienced substantially fewer fires than during 1985, the Eastern region did not show such great variability. (Table 4.1). Both of these maxima agree with the findings of LaDochy and Annett (1983) who found that high fire activity occurs in the northeast due to dense forest cover and in the area east of Lake Winnipeg because of relatively dense forest and a high frequency of thunderstorm activity. The southwest and south central parts of Manitoba with greatest thunderstorm activity but with sparse forest cover record very few fires.

Transferring the forest fire location data onto regions previously used in this study (Figure 3.5), the areas with the highest frequencies turned out to be the East Central, Southeast and Northern (West) regions, which had 60, 40 and 38 lightning-ignited fires, respectively (Table 4.2). The East Central and Northern (West) regions also had some of the largest fires (in 1985), three blazes accounting for two-thirds of total burned forest that year (66 800 hectares). Usually when blazes are ignited in remote areas where they pose no threat to humans or to valuable timber, the fires are simply monitored and allowed to burn themselves out, sometimes growing to enormous sizes and thus inflating figures for total area burned. Most fires of the East Central region were located in the southern half of that area (south of 53° N) and high incidence continued into the Southeast region, showing a concentration east and southeast of Lake Winnipeg. Fires in these two areas, especially, are suppressed because of the timber industry and many cottages (in the Whiteshell) where monetary losses would

Region District	1985	1986	Total
NORTHEAST			
Thompson	16	5	21
Leaf Rapids	6	1	7
Gillam	12	0	12
Norway House	10	10	20
Lynn Lake	7	3	10
God's Lake	9	0	9
Island Lake	13	4	17
Wabowden	3	4	7
Regional Total	**76**	**27**	**103**
NORTHWEST			
The Pas	0	1	1
Cranberry	3	1	4
Snow Lake	6	0	6
Regional Total	**9**	**2**	**11**
EASTERN			
Lac du Bonet	5	8	13
L. Winnipeg E.	17	17	34
Pine Falls	7	4	11
Bissett	6	2	8
Regional Total	**35**	**31**	**66**
INTERLAKE			
Riverton	2	0	2
Hodgson	2	2	4
Gypsumville	2	0	2
Grand Rapids	3	0	3
Regional Total	**9**	**2**	**11**
WESTERN			
Mafeking	0	1	1
SOUTHEAST			
Piney	7	1	8
Steinbach	0	6	6
Portage	0	1	1
Winnipeg	0	1	1
Regional Total	**7**	**9**	**16**

Table 4.1: Lightning-caused forest fires in Manitoba by Fire Management regions, 1985 and 1986. (Refer to Figure 2.5)

REGION	1985	1986	Total
NORTHERN (WEST)			
Thompson	16	5	21
Leaf Rapids	6	1	7
Lynn Lake	7	3	10
Regional Total	**29**	**9**	**38**
NORTHERN (EAST)			
Gillam	12	0	12
NORTH CENTRAL			
Norway House	10	10	20
Wabowden	3	4	7
Regional Total	**13**	**14**	**27**
EAST CENTRAL			
God's Lake	9	0	9
Island Lake	13	4	17
Lake Winnipeg E.	17	17	34
Regional Total	**39**	**21**	**60**
WESTERN 2 (NORTH)			
The Pas	0	1	1
Cranberry	3	1	4
Snow Lake	6	0	6
Regional Total	**9**	**2**	**11**
WESTERN 1 (SOUTH)			
Mafeking	0	1	1
INTERLAKE			
Riverton	2	0	2
Hodgson	2	2	4
Gypsumville	2	0	2
Grand Rapids	3	0	3
Regional Total	**9**	**2**	**11**
SOUTHEAST			
Lac du Bonet	5	8	13
Pine Falls	7	4	11
Bissett	6	2	8
Piney	7	1	8
Regional Total	**25**	**15**	**40**
SOUTH CENTRAL			
Steinbach	0	6	6
Portage	0	1	1
Winnipeg	0	1	1
Regional Total	**0**	**8**	**8**

Table 4.2: Lightning-caused forest fires in Manitoba by regions, 1985 and 1986. (Refer to Figure 3.5)

be greatest. In the North Central region, fires also were more common over the southeast quarter of that area, east of Lake Winnipeg.

4.1.2 TEMPORAL DISTRIBUTION OF LIGHTING-CAUSED FOREST FIRES

It has been demonstrated by LaDochy and Annett (1983) that the fire season in Manitoba corresponds with the summer thunderstorm season. Highest forest fire occurrences are in June, July and August. Comparing the frequencies of lightning days (Section 3.2) and forest fire days (a day which recorded a forest fire) reveals that July and August had the highest numbers of lightning days for both years. The greatest frequency of forest fire days occurred during those two months for 1985 (Figure 4.2a). For 1986, however, forest fire days were greatest in June and July rather than July and August (Figure 4.2b). Frequency of strikes was also greatest during July and August of both years, as was frequency of lightning-caused forest fires in 1985 (Figure 4.3a). But in 1986, June and July received the two highest numbers of forest fires while July and August experienced highest lightning frequencies (Figure 4.3b). Rainfall in the 1985 season was well below normal during July for both the north and south parts of Manitoba, and remained very dry in the north during August. The extremely dry conditions and extended periods of hot weather contributed to the forest fire problem that year. For the 1986 season, forest fire numbers were much lower, with peak levels in June and lower levels in July and

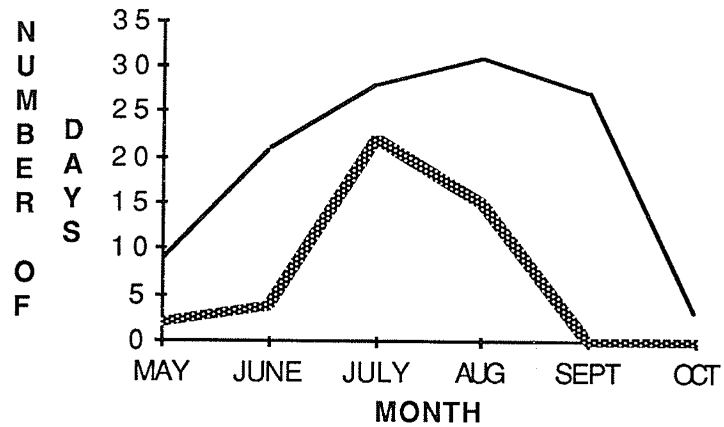


Figure 4.2a: Lightning Days and Forest Fire Days for Manitoba, 1985.

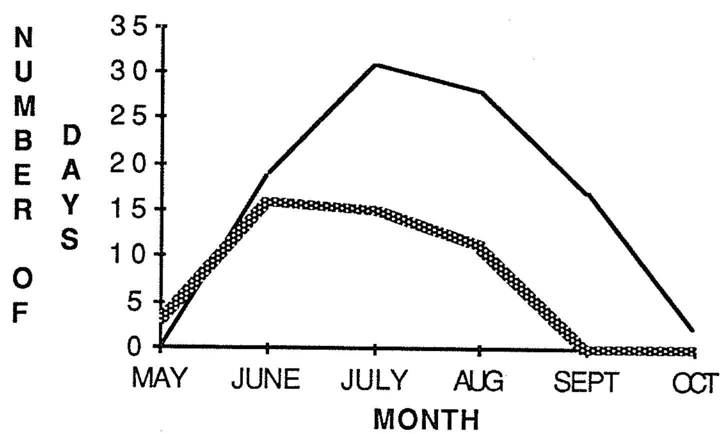


Figure 4.2b: Lightning Days and Forest Fire Days for Manitoba, 1986.

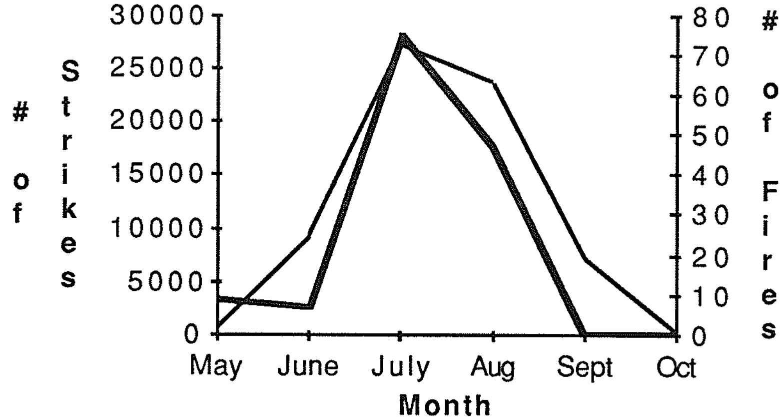


Figure 4.3a: Lightning Strike Frequency and Forest Fire Frequency for Manitoba, 1985.

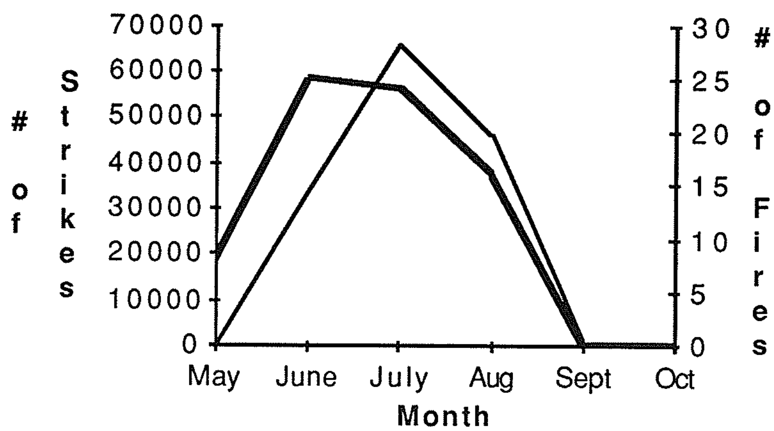


Figure 4.3b: Lightning Strike Frequency and Forest Fire Frequency for Manitoba, 1986.

August, possibly occurring due to a dry spring (in the south) and a wetter summer (Figure 4.1b).

The 1985 diurnal distribution of lightning-caused fires (Figure 4.4) derived from Manitoba Forestry reports of ignition time was compared with cloud-to-ground hourly strike frequency. Comparisons, however, are difficult as reported ignition time will not always correspond with the time lightning was actually in the area. Time of reported smoke may be some time after initial ignition by lightning. Generally, more fires were ignited (reported) in the afternoon hours as fires would be more visible in daylight. To some extent, then, forest fire ignition times did correspond with peak lightning strike times, though late night ignitions may be under-reported.

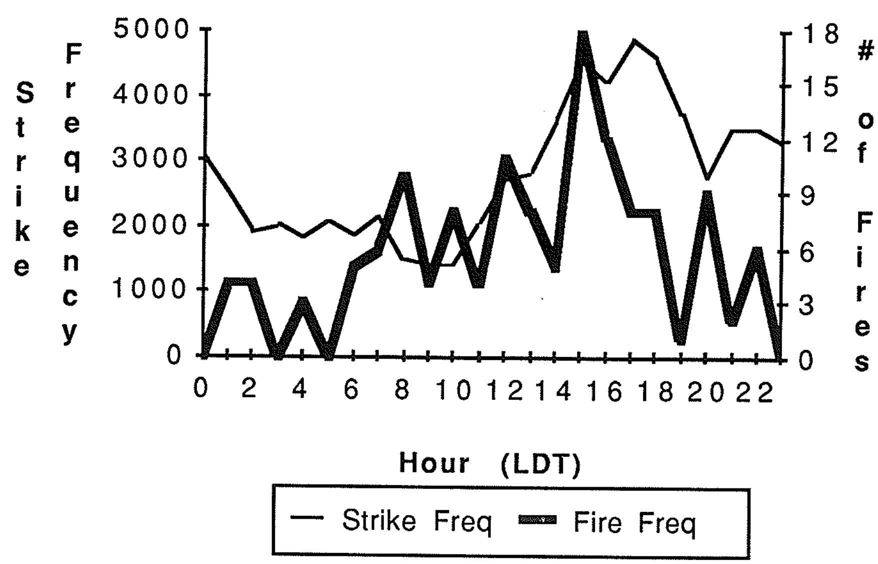


Figure 4.4: Hourly Distribution of Cloud-to-ground Lightning Strikes and Forest Fires, 1985.

Because the number of lightning-caused forest fires in any area can vary greatly from year to year, "to plan for the next fire season, an analysis of the fire history of [an area] is required" (Marsden, 1982). Knowledge of lightning strike distributions and severity can be used to "evaluate probable level of fire frequency to be encountered in a future year" (Marsden, 1982). Besides lightning activity, variables like fuel moisture, winds and precipitation make the interrelationship between lightning activity and forest fire hazard more complex.

Several individual lightning-caused forest fires started during case study storms will be briefly discussed in the following chapter.

4.2 HYDRO TRANSMISSION LINE DISRUPTIONS

Lightning strikes on or near electrical transmission lines are the main causes of power interruptions (Green, 1984; Bertness, 1980). This was the case for both 1985 and 1986 in Manitoba as 696 of 1202 power disruptions (57.9%) during a time from late May to the end of September were attributed to lightning in 1985 and 71.3% of 1183 in 1986. Manitoba Hydro keeps unpublished daily records of transmission line interruptions in load dispatcher's logs. This form provides information on the location, date and time of an interruption, as well as the length of time power was disrupted, voltage of the line affected by a failure and some brief, general comments about weather conditions and possible causes of the outage(s). These summaries are available for the three regions used by Hydro, Western, Central and Eastern (Figure 2.6) with each of the regions containing many smaller management districts. Often, it is known when an interruption is lightning-caused because of electrical current properties unique to such an event (Green, 1984; Popolansky, 1960). But many times it is assumed that if a thunderstorm was in an area which experienced interruptions, then the outages were classified as due to lightning even though this may not always be the case. Using lightning detector data in conjunction with the accounts of lightning-caused outages will provide some kind of verification of causes for interruptions.

Hydro data alone cannot show all interruptions caused by lightning strikes because the transmission lines are supplied with built-in safeguards, lightning arresters and surge divertors. Lightning arresters are basically lightning rods, which, if hit, lead the lightning down to the earth, grounding the strike. If the hydro pole's ground wire is not hit but a strike hits the actual overhead cable, then "it [strike's current] divides in two parts which travel along the line, half the current flowing in each direction" eventually producing an energy surge which "disrupts the flow of electricity" (Green, 1984). A detailed explanation of potential damage caused by a surge is found in Green (1984). Surge divertors located on transmission towers or within generating substations again divert a lightning strike into the ground. The vast majority of strikes do get grounded so that interruptions last less than one minute before automatic correction takes place. Because these minor disruptions are not recorded by Hydro, it is highly probable that transmitting systems are hit much more frequently by lightning than shown by the outage reports.

Most of the analysis involving power disruptions and lightning strikes was done using 1985 data. This is due to the incompleteness of 1986 strike data and awkwardness of using only 1986 hard-copy lightning maps with the hydro interruption reports.

4.2.1 SPATIAL DISTRIBUTION OF DISRUPTIONS

A spatial distribution of lightning-related power interruptions for 1985 (Figure 4.5) shows the majority of outages were concentrated in the southernmost part of Manitoba as would be expected because of the greater number of thunderstorms and higher density of transmission lines. The South Central and Southwest regions recorded the two highest frequencies and densities of outages (0.0133 and 0.0086 outages per km^2), while at the same time having two of the lower lightning strike densities (Figure 3.7). The Southeast showed the third highest outage density (0.005). For the remaining regions, outage density was always less than 0.001. Although having second highest lightning strike density, the Western 2 (North) region was not at all significant in terms of frequencies and densities of outages. In the South Central region, the city of Winnipeg provided just over half of reported outages. Brandon and Portage la Prairie, also accounted for a high percentage of reports. High densities of power disruptions in the south can be explained by a combination of the high concentrations of transmission lines in this most populated part of the province and high thunderstorm

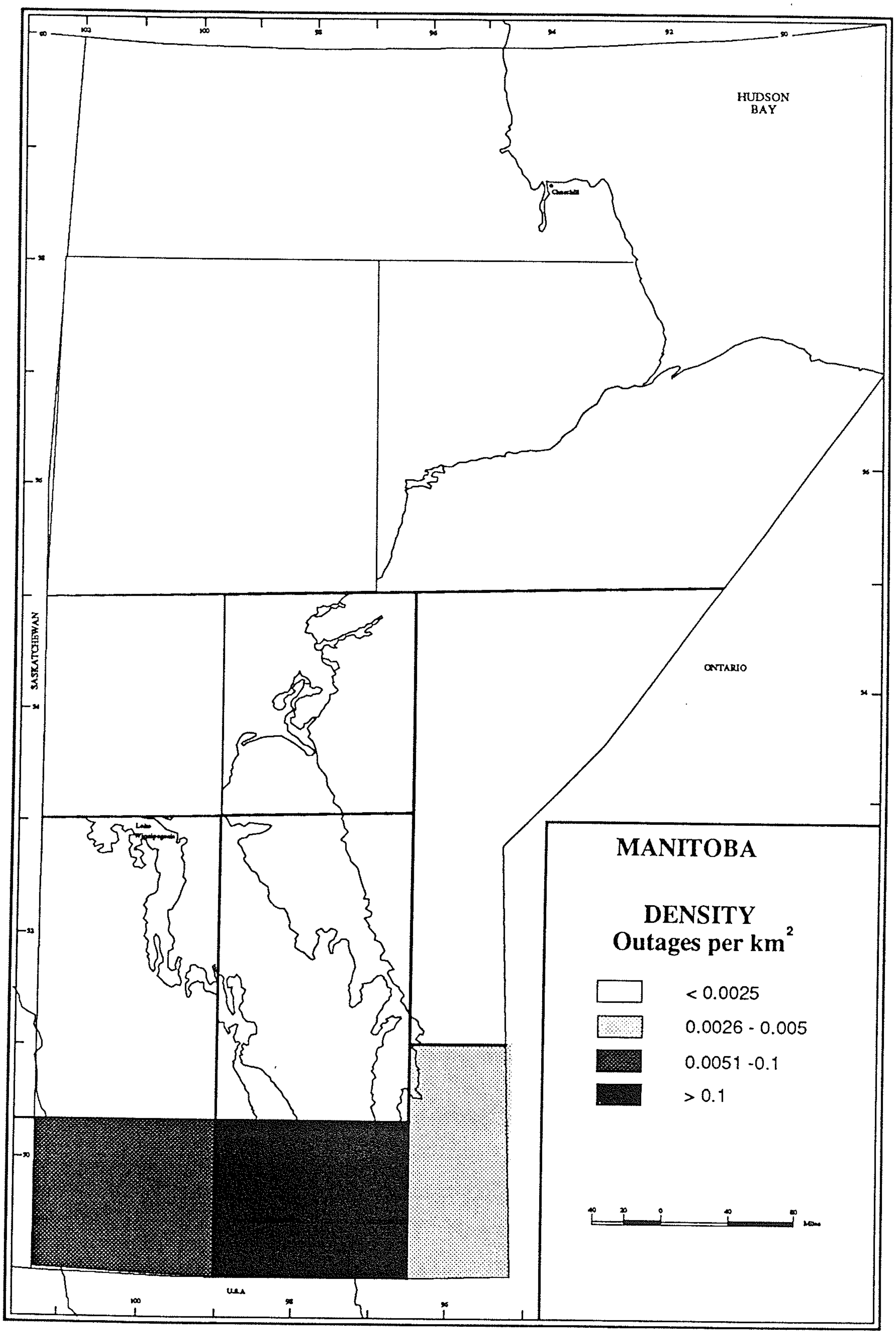


Figure 4.5: Lightning-caused Hydro Disruptions shown as number of Disruptions per km^2 for each region.

frequencies. Many more kilometres of lower voltage lines, which are more susceptible to hits by lightning, are also present here (LaDochy and Annett, 1983). For all regions, the greatest number of outages occurred for 66 kilovolts (KV) transmission lines with 33 KV and 115 KV lines having second and third greatest outages, respectively (Table 4.3). This corresponds with results found in previous work by LaDochy and Annett (1983). Because 66 KV lines are most common, it is not surprising that they appear more susceptible to outages.

	Voltage of Lines in KV					
Area	**24**	**33**	**66**	**115**	**138**	**230**
Central (incl. Wpg.)	23	40	156	42	1	4
Winnipeg only	23	16	89	18	NIL	3
Western	NIL	26	128	11	NIL	NIL
Eastern	NIL	38	74	43	12	NIL
Total	23	104	358	96	13	4

Table 4.3: Lightning-caused Power Interruptions for Manitoba Hydro Management Regions by Voltage of Transmission Lines, 1985.

4.2.2 TEMPORAL DISTRIBUTION OF DISRUPTIONS

The 1985 frequency of lightning-caused outages (Figure 4.6) showed a general increase of interruptions for the province as a whole throughout the summer months, peaking in August. The Central and Eastern hydro regions also showed this same pattern but for the Western region, a noticeable drop in disruptions occurred during July, increasing to maximum values in August. August 3 caused a dramatic leap in values for all regions since just over one-quarter of lightning-caused interruptions occurred on this date. The frequency distribution of the 1985 disruptions, however, did not follow strike frequency (Figures 4.6 and 3.9). The number of days with interruptions and lightning days (Figures 4.7 and 3.10) also did not correspond. Highest strike numbers occurred in July, then August while greatest number of disruptions were recorded in August, then July. The more active lightning days produced the higher August frequency for outages. Even after examining strike frequencies for the southern part of Manitoba (South Central, Southwest, Western 1 (South) and Southeast regions), July still recorded highest lightning frequencies (Table 4.4). In the south, August logged the most disruption days with July second, this pattern coinciding with lightning days (Figure 4.7 and Table 4.5).

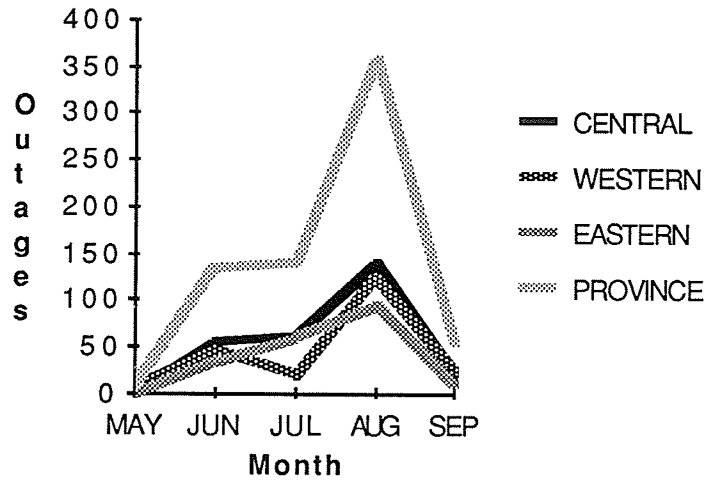


Figure 4.6: Seasonal Frequency of Lightning-related Power Disruptions for Manitoba Hydro Management Regions, 1985.

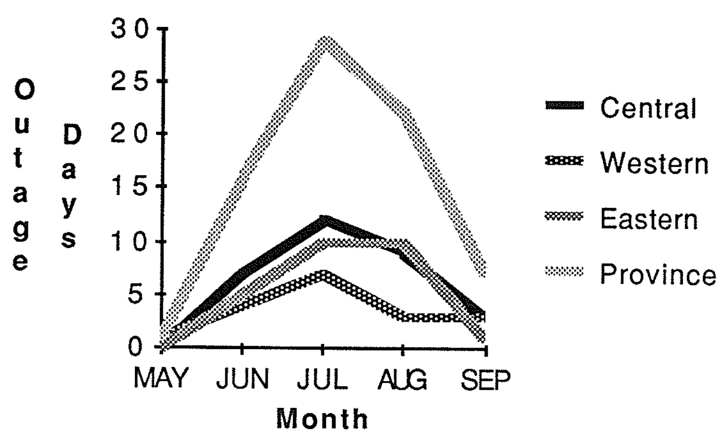


Figure 4.7: Disruption Days for Manitoba Hydro Management Regions, 1985.

Month	Frequency
May	469
June	2 772
July	6 879
Aug	6 289
Sept	4 372

Table 4.4: Strike Frequencies for Southern Manitoba, 1985.

Month	Frequency
May	9
June	20
July	28
Aug	30
Sept	25

Table 4.5: Lightning Days for Southern Manitoba, 1985.

Diurnally, outages were more common between 1600 and 2300 LDT with a secondary maximum occurring between 0400 and 1000 LDT. Fewest outages occurred during the midday hours (1100 to 1500 LDT) (Figure 4.8). Comparing these data with diurnal lightning strike data (Figures 3.12a and b), the later day maximum corresponded with the pattern of lightning strikes in northern and southern Manitoba while the night peak and to a lesser degree the early morning peak corresponds only to the southern Manitoba pattern of lightning strikes.

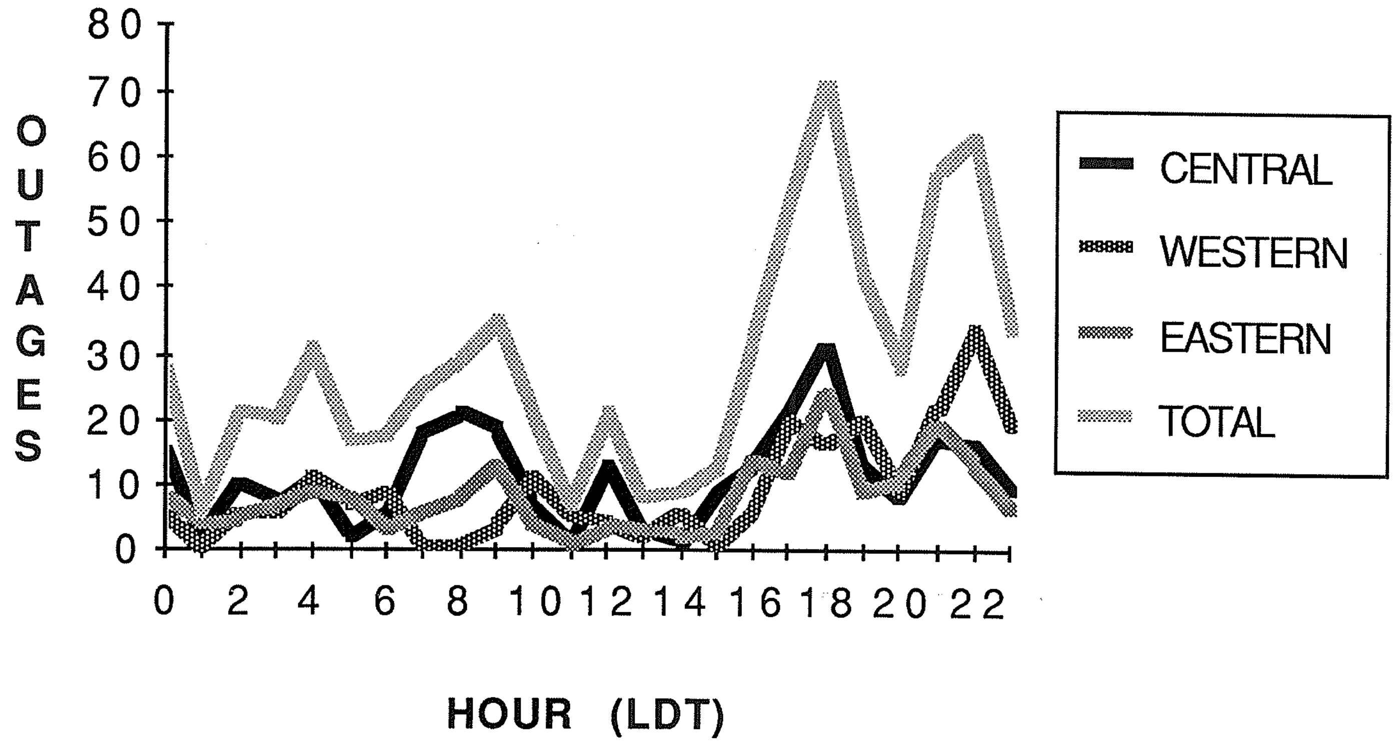


Figure 4.8: Hourly Distribution of Power Disruptions for Manitoba Hydro Management Regions, 1985.

Because hydro outages did not correspond well with general lightning strike spatial and temporal distributions due to poor DF coverage in the south, only brief and general comments on outage events and patterns in relation to strike distributions during case study storms will be discussed in the following chapter.

It is difficult to relate the kinds of data discussed in this chapter without more detailed information. Forest fires occur in areas of moderate to good detector coverage, but hydro reports are heavily biased to the south and Winnipeg, where lightning detector records are poor. Forest fires have some problems of comparisons because of other external controlling factors. Preliminary, general comparisons between forest fires or hydro disruptions and lightning strike distributions are used more as two examples of the application potential of detector data rather than to give conclusive results. With improved, increased coverage by DFs, to show where lightning is frequent, a better estimate of high risk forest fire and hydro disruption areas will be able to be determined.

CHAPTER 5

CHARACTERISTICS OF CASE STUDY LIGHTNING STORMS

While lightning was recorded on 122 days in 1985 and 94 days in 1986, most strikes occurred during a few very active storms. With a combined two year total of 221 485 cloud-to-ground strikes, 68.2% of strikes were recorded during 31 storm days (Table 3.1). These active storms were the most important since they were usually responsible for many lightning-caused forest fires, power outages, damaging winds and occasional hail or tornadoes. Several storms are chosen to be discussed in some detail as examples.

The selected case studies are those that produced 1 500 or more cloud-to-ground strikes. The 31 storm dates from 1985 and 1986 are then classified into types based on surface weather conditions and the 250 millibar (mb) jet axis direction nearest to the times of maximum lightning activity and nearest the storm using categories previously defined by Lowe and McKay (1961) and also modified by LaDochy (1985). While LaDochy (1985) only looked at the direction of the jet stream wherever it was nearest to the storms, because of small sample size, this analysis uses jet stream direction whether or not the axis was close to storms. For selected case study storms, lightning frequency, time and location of maximum activity, as well as some synoptic features are noted. Spatial relationships between the distribution of lightning and surface frontal features are also generally described. Synoptic groupings are decided with greater emphasis placed on surface characteristics because those are more convenient to use and have greater resolution and information. Although the synoptic type categories used were defined for tornado and hail occurrences, they are useful for a preliminary breakdown of some similar synoptic features among the lightning storms.

5.1 SYNOPTIC CLASSIFICATION

Storms are first individually classified by dominant surface features into one of four categories, Type A, B, C or D, as defined by Lowe and McKay (1961). Type A refers to a situation where a north-south cold front is present with an instability line ahead of it producing severe weather. Type B is very similar to Type A except that the frontal wave is better developed with a well-defined warm front and storms occurring north of the frontal wave. Southward-moving, well-defined cold fronts represent the surface synoptics for Type C. The final category, Type D occurs where severe weather is present in a northwest flow of air. Once storms are classed by surface features, jet axis orientation is determined. Three secondary categories are defined by LaDochy (1985) for 250 mb jet axis direction. If the upper level jet comes from the west, storms are classed as Type 1. When the jet tends to blow from the northwest or north, Type 2 is chosen. Type 3 accounts for jet flow from a south or southwest direction. Table 5.1 shows results of the separate groupings. Types A and B predominate (Table 5.1a)

SURFACE TYPE	Frequency
A	19
B	9
C	2
D	1

5.1a: Surface Type Frequencies

JET TYPE	Frequency
1	8
2	6
3	17

5.1b: Jet Type Frequencies

FINAL SYNOPTIC TYPE	Frequency
A1	7
A3	12
B1	1
B2	3
B3	5
C2	2
D2	1

5.1c: Synoptic Type Frequencies

Table 5.1: Frequencies of Synoptic Classes Associated with 1985 and 1986 Lightning Storm Days.

agreeing with the results of Lowe and McKay (1961) and LaDochy (1985) for tornadic severe thunderstorms. As in the two previous works, Type A accounted for more of the larger lightning storms. Jet-level winds from the south or southwest (Type 3) are most dominant for these lightning storms also agreeing with previous results for tornado and hail occurrences (Table 5.1b).

Combining the information from surface features and jet direction, a final synoptic type classification is derived (Table 5.1c). For the selected lightning storms, Type A3 is the most frequent category (38.7%), Type A1 being a distant second (22.6%). LaDochy (1985) found Type A3 but then B3 to account for the most and second most frequent groups, respectively, for tornado and hail incidents.

In the following sections, each of the four synoptic types will be summarized. Then, some of the more typical lightning storms will be examined in detail. Composite maps showing strike locations and areas with forest fires, hydro disruptions and severe weather are produced, with the synoptic features that probably contributed most to incidents of high cloud-to-ground lightning frequencies being highlighted for the selected examples. For each example, the three most lightning-active regions are determined. Strike direction, the direction from which strikes are moving will also be identified. Due to the small sample size and because weather variables are so changeable from one storm to the next, the discussion in this chapter is limited to descriptions of storms. From the synoptic classifications and descriptions of lightning storms, some preliminary synoptic information on cloud-to-ground lightning characteristics in Manitoba will be provided.

5.2 ANALYSIS OF SYNOPTIC TYPES

5.2.1 TYPE A (19 DAYS)

Type A lightning storms experienced a range from just over 1 700 to more than 14 000 cloud-to-ground strikes (Table 5.2). Both the highest and lowest frequency case days were Type A1, most strikes occurring on June 25, 1986 (14 364) and least on July 27, 1985 (1 782). The Western 1 (South), Southeast, Interlake and Northern (West) regions showed highest lightning activity for the Type A group. Close to three-quarters of dates recorded more lightning north of the jet axis with two days showing no preference. For most cases, strike clusters were oriented in a westerly or southwesterly direction. June 11, 1986, for example, showed strikes oriented in two directions indicated by SW/W on Table 5.2.

Forest fires were recorded on 11 of the 19 Type A events contained in Table 5.2. Seven dates with no fires occurred during 1986, including July 29 with the second greatest number of strikes of all case dates. Some form of lightning-initiated power outage was reported for all but one day, July 22, 1986. When a "+" appears with the outages, more than 20 disruptions occurred. The date with lowest frequency recorded more than 20 outages. Six Type A dates are listed in the AES *Summary of Severe Weather Bulletin* but none of the 1985 days recorded any incidents of hail, heavy precipitation or tornadoes.

Date		Type	Total Freq	Most Active Region[1]	Lightning North or South of Jet: North	South	Direction of Strikes	Occurrence of: Forest Fire	Hydro Outage	Severe Weather
1985										
July	12	A3	2 701	West2	X	X	NW	X	X	
	23	A3	4 061	SE	X		SW	X	X	
	27	A1	1 782	West1	X		W	X	X	
Aug	5	A1	7 091	Nor(W)	X		WSW	X	X	
	26	A1	3 701	Int	X		N/A	X	X+	
Sept	5	A3	1 569	SE	X		NW		X+	
1986										
June	11	A3	7 281	West2	X	X	SW/W		X	
	19	A3	>3 000	S.Cen		X	SW		X+	X
	25	A1	14 364	Int		X	W	X	X	
July	3	A3	5 159	SW	X		SW	X	X+	X
	5	A3	4 040	S.Cen		X	SSW/W	X	X+	
	22	A1	3 183	Nor(W)	X		SW/W	X		
	23	A3	6 214	E.Cen		X	SW		X	X
	25	A3	6 808	West1	X		W		X+	X
	28	A3	6 315	SE	X		SW	X	X+	
	29	A3	12 971	Int	X		W		X+	
Aug	13	A1	4 257	West1		X	SW/NW	X	X	X
	14	A1	3 223	Nor(W)	X		SW		X	
	19	A3	7 919	Nor(E)	X		NW/SW		X+	X

+ indicates more than 20 outages

Table 5.2: Summary of Type A Lightning Storms.

[1] See APPENDIX 2 for key to abbreviations.

5.2.2 TYPE B (9 DAYS)

Type B storms recorded a range of 1 988 to 10 545 strikes (Table 5.3). Only one storm was classified as Type B1, causing some extensive damage. Areas with high lightning activity included the Western 2 (North) and Interlake regions. The Southeast region also experienced some intense activity. During five of the nine cases, lightning could be identified as occurring north of the jet axis. As with Type A events, most strikes travelled from a west or southwest direction.

Six days recorded forest fires. July 2-3, 1985 with 15 fires burned thousands of hectares. All days but one, June 21, 1986, experienced lightning-caused power disruptions. August 3, 1985 logged over 150 interruptions. Severe weather, including heavy rain, hail and tornadoes was logged on five days.

5.2.3 TYPE C (2 DAYS)

Two days, August 7 and 8, 1986 were grouped into Type C, both being Type C2 (Table 5.4). For each day, a west-east oriented cold front was advancing south across the province.

Most strikes occurred in the Interlake and North Central regions, clustering over the north basin of Lake Winnipeg and between Lake Manitoba and the south basin of Lake Winnipeg. The area of strikes was north of the 250 mb axis.

Heavy precipitation in the Interlake and North Central regions probably helped with forest fire suppression as no fires were

Date		Type	Total Freq	Most Active Region[1]	Lightning North or South of Jet: North	South	Direction of Strikes	Occurrence of: Forest Fire	Hydro Outage	Severe Weather
1985										
June	20-21	B3	3 422	West2	X		SW/NW		X	X
July	2-3	B2	10 545	Int	X		WNW	X	X+	X
	15	B2	2 475	West2	X		W	X	X	
Aug	3	B3	2 061	SE		X	SW	X	X+	
	31	B3	2 567	E.Cen	X		W		X	
1986										
June	21	B3	1 988	E.Cen	X		SW	X		X
	24	B1	3 889	West2		X	WNW	X	X	X
July	17	B3	4 186	SE		X	W/WSW	X	X+	
Aug	6	B2	6 779	Int		X	SW		X+	X

+ indicates more than 20 outages

Table 5.3: Summary of Type B Lightning Storms.

[1] See APPENDIX 2 for key to abbreviations.

Date	Type	Total Freq	Most Active Region[1]	Lightning North or South of Jet: North	South	Direction of Strikes	Occurrence of: Forest Fire	Hydro Outage	Severe Weather
1986									
Aug 7	C2	2 842	Int	X		NW		X	
8	C2	2 119	Int	X		NW		X	X

Table 5.4: Summary of Type C Lightning Storms.

Date	Type	Total Freq	Most Active Region[1]	Lightning North or South of Jet: North	South	Direction of Strikes	Occurrence of: Forest Fire	Hydro Outage	Severe Weather
1986									
Aug 3	D2	8 806	N.Cen	X		NW	X	X+	

+ indicates more than 20 outages

Table 5.5: Summary of Type D Lightning Storm.

[1] See APPENDIX 2 for key to abbreviations.

ignited. Several brief power disruptions occurred and a localized incident of hail was recorded in the southwest on August 8.

5.2.4 TYPE D (1 DAY)

Only one date, August 3, 1986 was classified as a Type D2 storm (Table 5.5), associated with a northwest flow of air. Lightning storms began about 1400 LDT, with the highest density of strikes occurring just north of the Lakes in the North Central region, a couple of hours later. Storms still continued in the late afternoon and at night, mainly in the north and western edges of the province.

Two forest fires were ignited by lightning in the Thompson and Lynn Lake areas and one near Steinbach. While no severe weather was recorded, 26 lightning-caused power disruptions occurred.

5.2.5 SUMMARY

Due to the small sample size, considerable variability is seen within the two main groups (Types A and B) making it difficult to summarize the general findings. This also applies to the sub-categories with at least five examples (Types A1, A3 and B3). Both similar and contrasting characteristics can be observed for each type but no one variable could be isolated as a primary factor to cause some storms to produce a higher frequency of strikes than others.

Tables 5.6a and b rank regions of high lightning frequencies for Type A and B storms. For each storm, three regions which are the most lightning-active areas are extracted (APPENDIX 2). Selections

REGION	Weights by Frequency of Strikes			SCORE	OVERALL RANK
	First	*Second*	*Third*		
Western1(S)	**3**	**4**	**3**	**20**	**1**
Southeast	3	3	1	16	2
Interlake	3	1	5	16	3
Northern(W)	3	1	1	12	4
Southwest	1	4	1	12	5
East Central	1	3	2	11	6
Western2(N)	2	1	2	10	7
South Central	2	1	1	9	8
Northern (E)	1	0	2	5	9
North Central	0	1	2	4	10

a: Type A Lightning Storms.

REGION	Weights by Frequency of Strikes			SCORE	OVERALL RANK
	First	*Second*	*Third*		
Interlake	2	4	0	14	1
Western2 (N)	3	1	1	12	2
East Central	2	1	1	9	3
Southeast	2	1	0	8	4
Western1 (S)	0	0	4	4	5
Northern (W)	0	1	0	2	6
Southwest	0	1	0	2	7
North Central	0	0	2	2	8
South Central	0	0	1	1	9
Northern (E)	0	0	0	0	10

b: Type B Lightning Storms.

Table 5.6: The Number of Type A and B Storm Dates by Regions having the Highest, Second and Third Highest Lightning Activity for that Date.

for 1985 storms are based on calculated strike densities in the regions. Visual inspection is used to determine most active regions for 1986 storms as densities could not be calculated because actual frequencies could not be obtained for that year. Regions are ranked according to the number of times they appear as the most active, second-most active and third most active areas. A value of three is assigned to each time a region experiences highest lightning activity. Every time a region experiences the second highest activity, two is assigned and one is given for each third place position. The weighting values are summed for each region, the higher total score provided an indication of greater susceptibility to high lightning densities. Thus, the highest scoring region is ranked as **"1"**, most susceptible to lightning. The second highest scoring region is ranked as **"2"**, second most susceptible to lightning. This process continues until all regions are ranked.

Using Type A storms and the Western 1(South) region as an example (Table 5.6a), three storm dates have maximum lightning activity in this region indicated under the "First" column. Then, four storm days experience second highest lightning activity in this area ("Second" column) and finally, three storms experience third highest lightning activity in the area ("Third" column). Each occurrence in the "First" category receives a score of three, giving a sum of nine for this example. Two is assigned to each occurrence in the "Second" category, giving a sum of eight. The "Third" category gets a score of one for each occurrence, giving a sum of three. Adding the scores for each category gives a total of 20. This is the highest scoring region in Type A, putting the Western 1(South) region as the area most susceptible to lightning activity with a rank of **"1"**. The Southeast receives a rank of **"2"** and the Interlake is ranked as **"3"**. Each of the top three ranked areas experiencing most strikes for Type A storms have been identified previously (Section 3.1) as high frequency and density locations. For Type B examples, two of the same areas identified earlier in Section 3.1, namely the Interlake and Western 2 (North) regions record most lightning activity. The East Central, then Southeast region also figure prominently, placing third and fourth in this ranking.

During Type A storms, lightning ignited 42 fires (Table 5.7a). But Type B, with 22 forest fires (3.7 fires per storm), burned thousands of more hectares. During lightning storms, the East Central, Northern (West) and Southeast regions were most susceptible to forest fires, and Type A3 storms were responsible for 20 of 32 fires in the two eastern areas. In the Western 2 (North) region, the majority of fires occurred with Type A1 storms. While Types A1 and A3 storm days were responsible for the loss of 412 and 1 857 hectares of forest, respectively, Type B2 forest losses totalled over 12 000 hectares (Table 5.7b). One storm, July 2-3, 1985 was responsible for most of that loss (APPENDIX 3). Other factors like wind and rainfall, for instance, of course played roles in the forest fire events. If the July 2-3 Type B2 storm was eliminated from the sample, the large differences among the categories disappear.

Region	Storm Type A1	A3	B1	B2	B3	D2
South Central		1				
Southwest						
Southeast	2	9	1		1	1
Interlake	1	1				
Western1(S)						
Western2(N)	7			3		
East Central	4	11			2	
North Central		2		2	1	
Northern(W)	3	1		8		2
Northern(E)				3	1	
TOTAL FIRES	17	25	1	16	5	3

Table 5.7a: Forest Fire Frequency for Each Synoptic Storm Type.

	Storm Type A1	A3	B1	B2	B3	D2
Area Burned (In Hectares)	412	1 857	1	12 326	56	59

Table 5.7b: Forested area burned for Each Synoptic Storm Type.

Hydro Disruptions	Storm Type A1	A3	B1	B2	B3
Total	86	393	5	59	261
Average	(14.3)	(32.8)	(5)	(19.7)	(65.3)

Table 5.8: Frequency of Power Disruptions for Each Synoptic Storm Type.

For hydro disruptions (Table 5.8), Types A3 and B3 recorded 393 and 261 incidents, respectively, with August 3, 1985 accounting for 174 of B3 interruptions. Type A1 was a distant third with only 86 incidents. Determining average number of interruptions per storm for each class, Type B3 received the greatest value of 65.3 disruptions per storm, Type A3 being second with 32.8 and Type D2 third with 26. Again, if the extreme (August 3) was ignored, giving an average of 29 for Type B3, then differences are reduced.

Severe weather events also occurred with some storms and not others (Table 5.9). A total of 34 incidents of severe weather were recorded during the sample days, five occurring during the only two 1985 storms. With five days and 21 severe weather events, Type A3 storms caused most damage mainly because of strong winds or tornadoes. Generally, most severe weather was found in southern Manitoba and occurred with Type A3 storms, agreeing with previous work (LaDochy, 1985). Calculating average number of incidents per storm for each type, Type A3 received most incidents with an average of 4.4 severe weather events per storm. Type B1 with three incidents per storm was second and Types A1 and B2 with two incidents were third.

Storm Type	Date		Region	Event
A1				
	Aug	13/86	Interlake	Hail
			Western1(S)	3" Rain
A3				
	June	19/86	South Central	Wind; Hail
			Southwest	Wind
			Western1(S)	Wind; Tornado
	July	3/86	South Central	Wind (2 cases)
			Southwest	Wind (2 cases); 3-3.5" rain
	July	23/86	South Central	Tornado
	July	25/86	South Central	59 mm rain in 45 min.
			Southwest	Wind; Tornado
	Aug	19/86	South Central	Hail
			Southwest	Hail; Tornado (2 cases)
			Southeast	Hail
			Western1(S)	Hail (2 cases)
B1				
	June	24/86	Western1(S)	Rain; Wind (2 cases)
B2				
	July	2-3/85	Southeast	Wind; Tornado
			Interlake	Hail
	Aug	6/86	Western1(S)	Wind
B3				
	June	20-21/85	Southwest	Hail; Rain
	June	21/86	Interlake	Wind
C2				
	Aug	8/86	Southwest	Hail

Table 5.9: Incidents of Severe Weather for Each Synoptic Storm Type by Region. (Summary of Severe Weather Bulletin; AES)

5.3 SELECTED LIGHTNING STORM EXAMPLES

Selected typical lightning storms from the major synoptic types are chosen for some detailed review. Lightning locations, strike orientation, number of forest fires, hydro disruptions and severe weather events are mapped. Figure 5.1 provides explanation of the symbols used in these maps.

5.3.1: Type A1: August 5, 1985 (Figures 5.2a and b)

With a total of just over 7 000 strikes associated with this event (Table 5.1), about 92% were found in the western part of Manitoba. The Northern (West) region experienced greatest strike densities. Clusters of strikes were found in the Interlake, mainly over Lake Winnipeg's north basin. Strikes are primarily north of the jet axis. The surface frontal wave was travelling in a northeasterly direction with strikes concentrated around the wave apex and roughly along the cold front line. Temperatures were quite hot, close to 30° C by afternoon, even in northern Manitoba. Dewpoint temperatures (Tds) also reached high values throughout the province.

Little precipitation was recorded, especially at the more northerly stations. The lack of rainfall probably contributed to the ignition of seven fires in the northwest. Three power outages occurred on high voltage transmission lines in the Thompson area but no reported, severe weather accompanied this system.

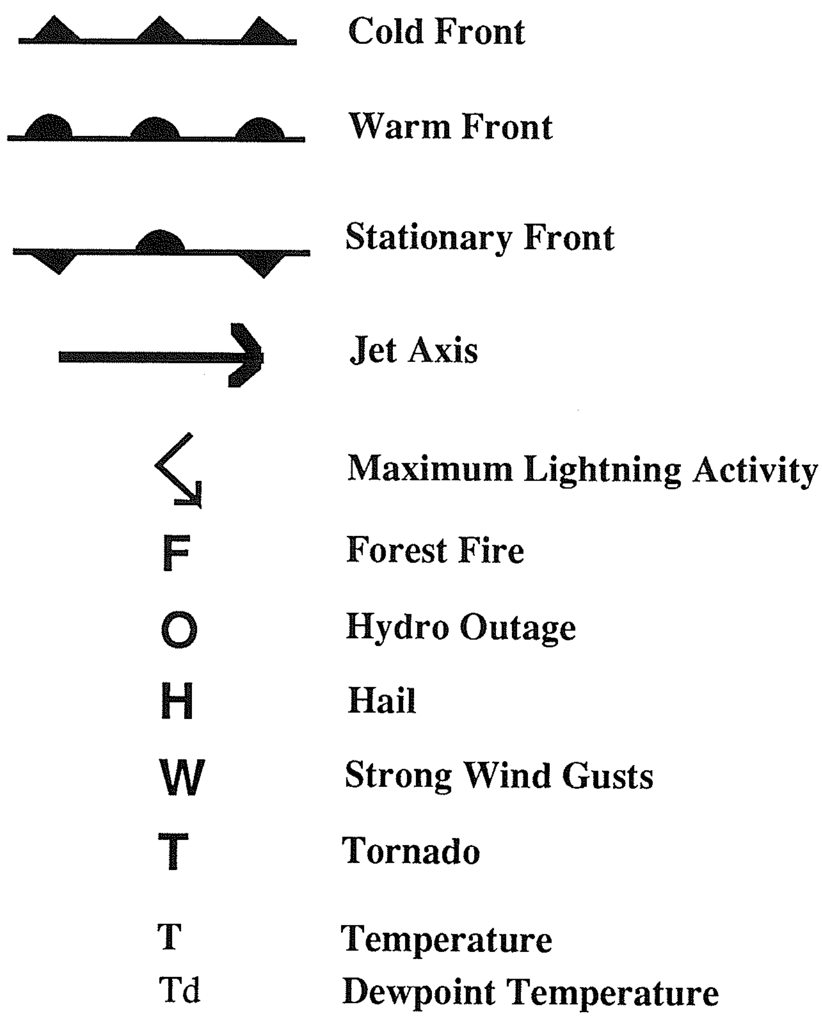


Figure 5.1: Symbols used on Lightning Storm Maps.

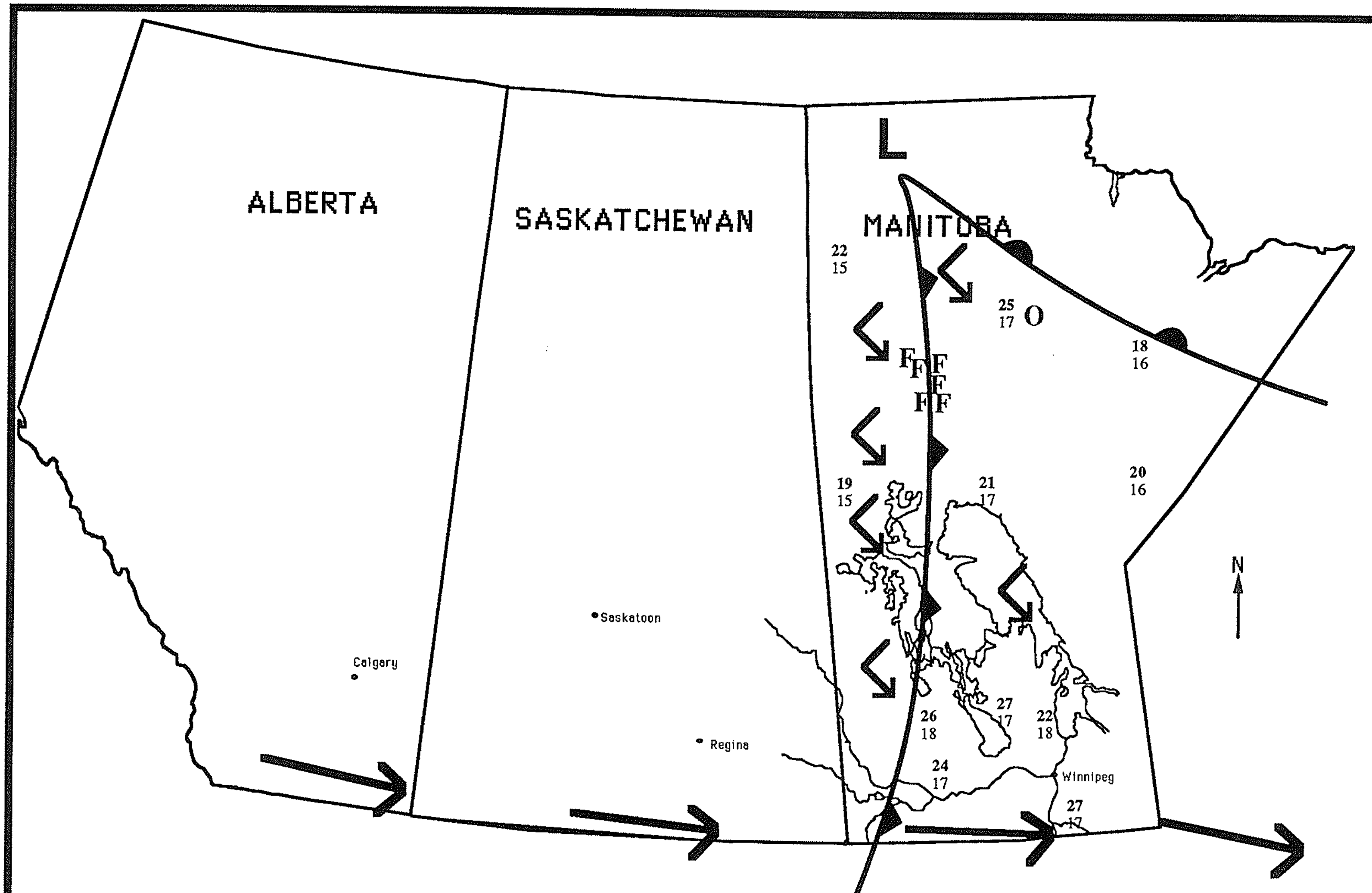


Figure 5.2a: Example of Type A1 Lightning Storm: August 5, 1985, 1700 LDT (7 091 Strikes).

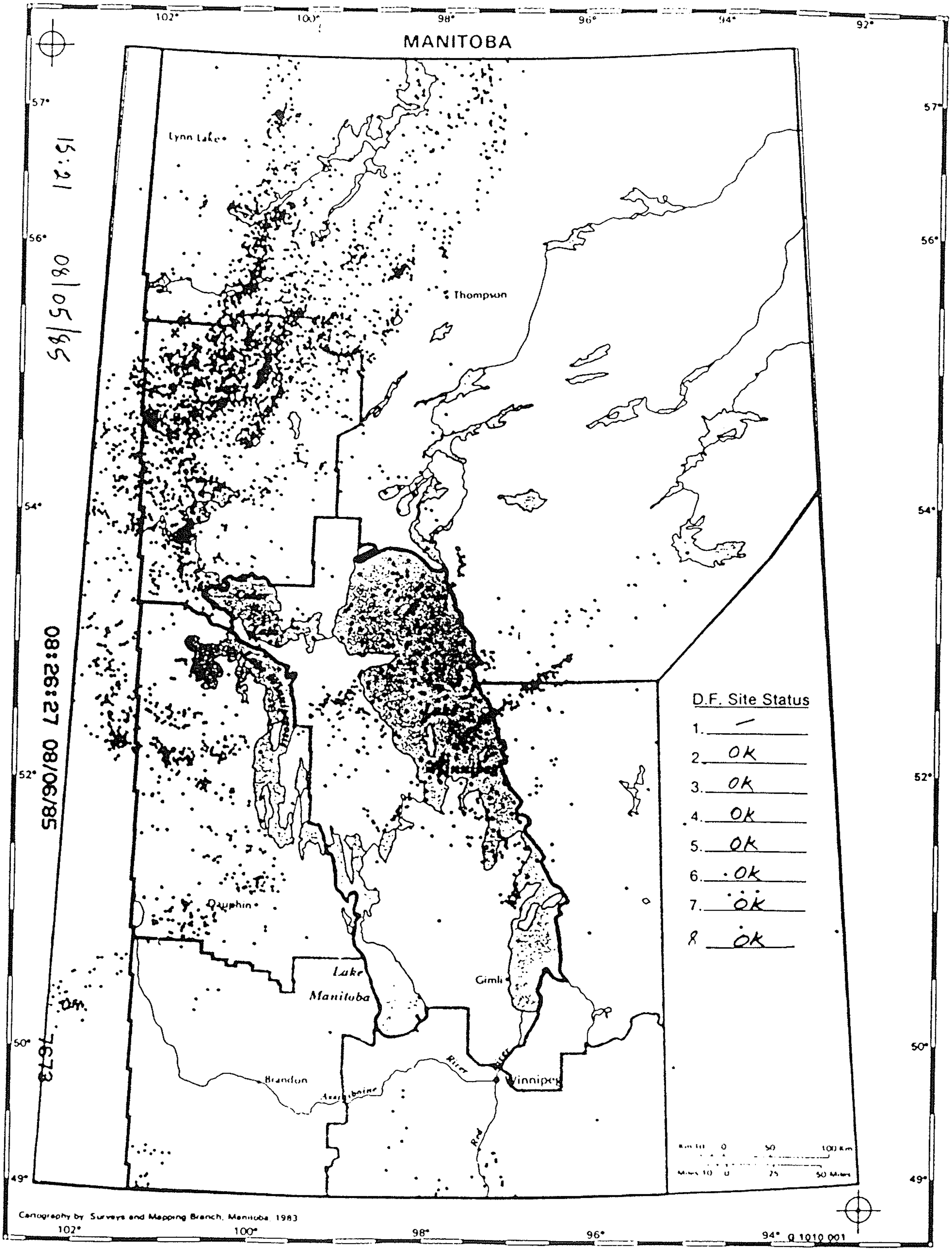


Figure 5.2b: Lightning Strike Distributions: August 5, 1985.

5.3.2: Type A3: July 29, 1986 (Figures 5.3a and b)

With almost 13 000 strikes, the second highest of all cases, July 29, 1986 storms began around 1600 LDT and continued well into the night (2300 LDT). An occluded front dominated at first, quickly forming into a frontal system albeit not particularly well developed. Lightning activity occurred south of the stationary frontal system in the warm sector. In this warm sector, temperatures were hot and it was very humid. Tds in the southeast portion of the province were all greater than 16° C. Densest concentrations of lightning occurred in the Lake Manitoba area and just west of it later at night (2200 LDT) alongside the north-south oriented cold front boundary. As was the case earlier in the day, lightning was also located south of the frontal wave. The progression of lightning appeared roughly as bands parallel to the 250 mb winds.

No forest fires were reported that day, partly because of significant precipitation in the southeast. However, 59 hydro disruptions occurred, all in southern Manitoba. This value of 59 was the highest for Type A3 for one day.

5.3.3: Type B2: July 2-3, 1985 (Figures 5.4a and b)

With the third highest strike frequency of all case study days, July 2-3, 1985 was also very active in terms of the amount of damage. Strikes were concentrated in a number of localities, high density centres appearing in the Interlake at night (July 2, 2200 LDT), Western 1 (South) region in the early morning (July 3, 0500 LDT), North Central and East Central regions in the evening and night

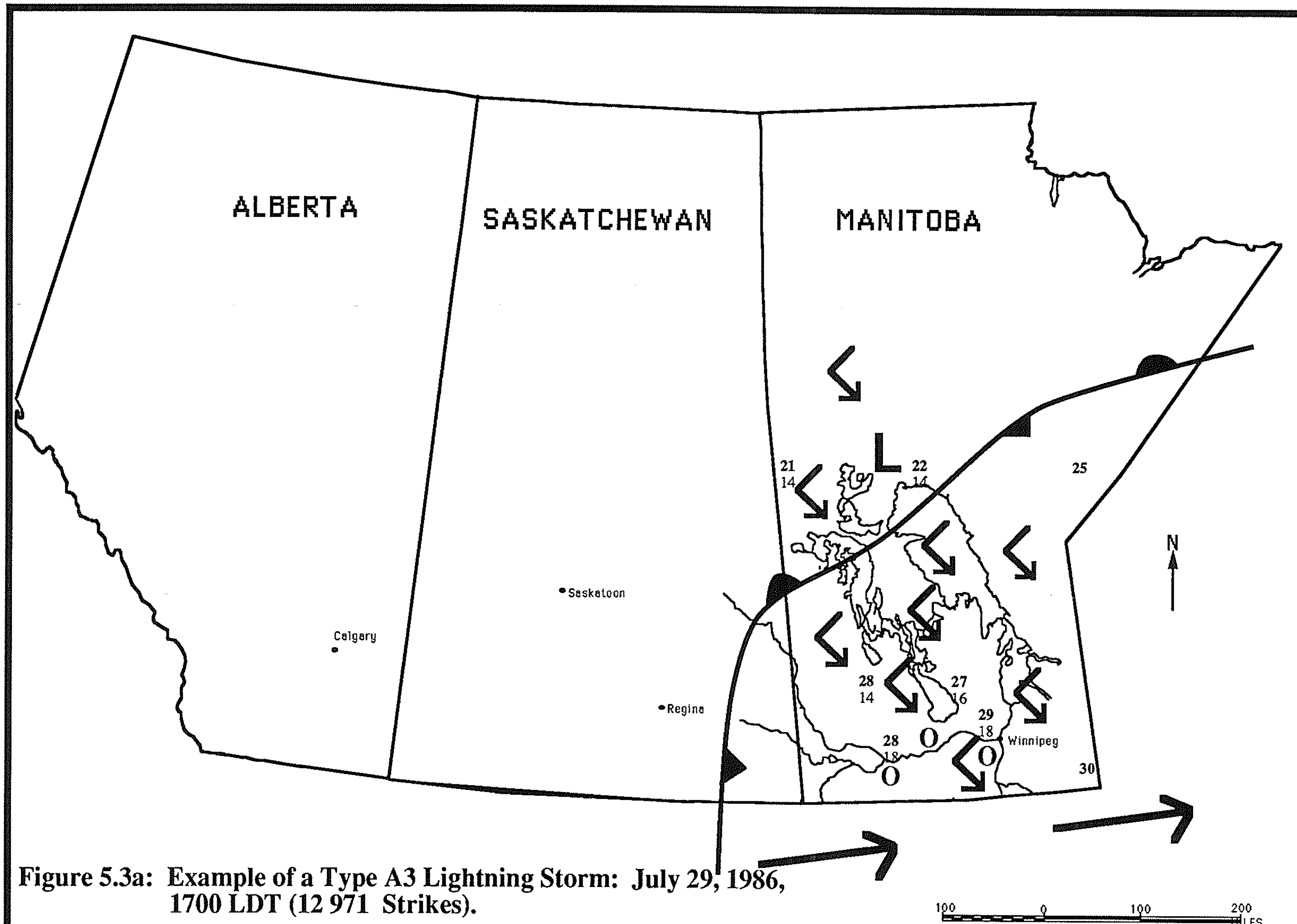


Figure 5.3a: Example of a Type A3 Lightning Storm: July 29, 1986, 1700 LDT (12 971 Strikes).

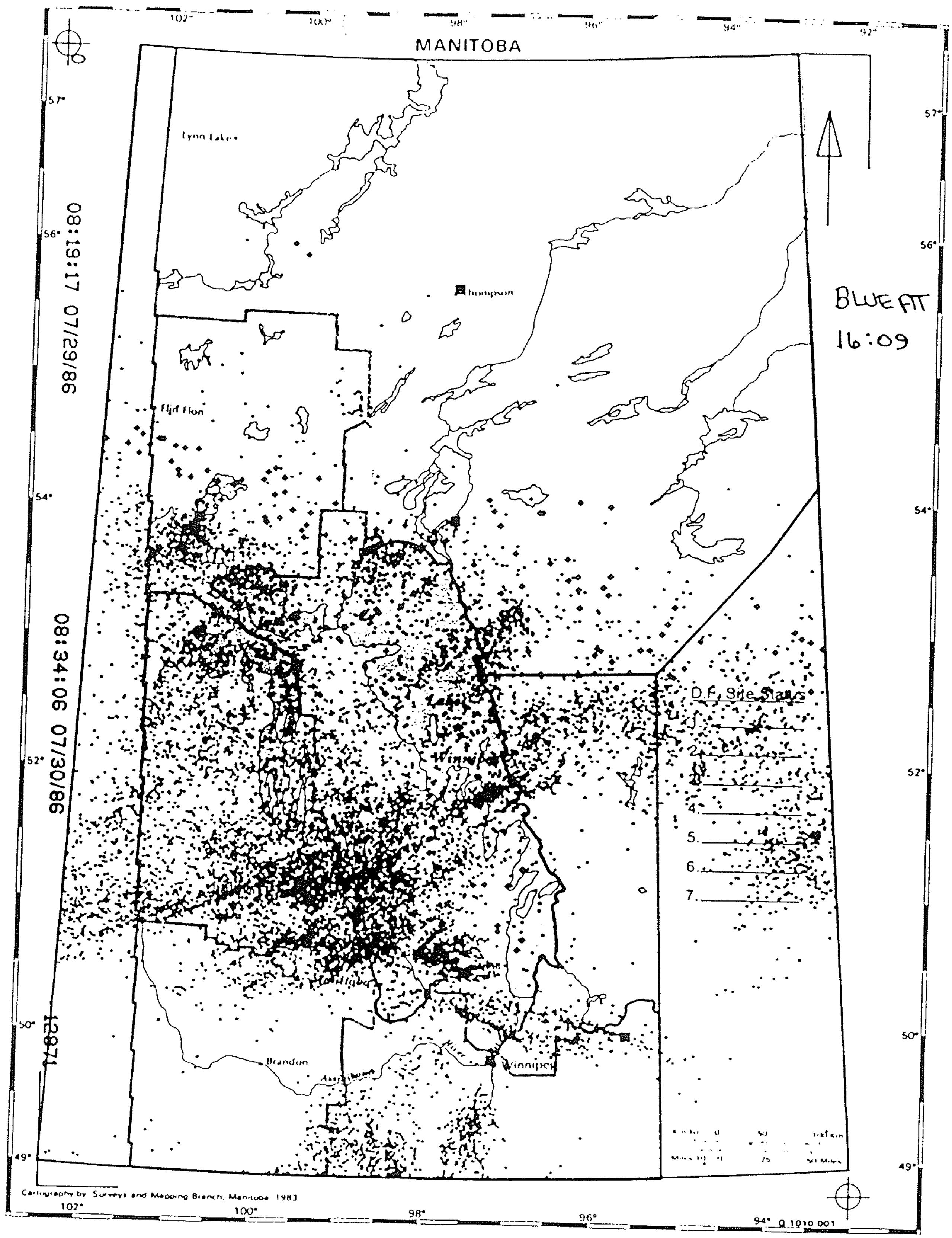


Figure 5.3b: Lightning Strike Distributions: July 29, 1986.

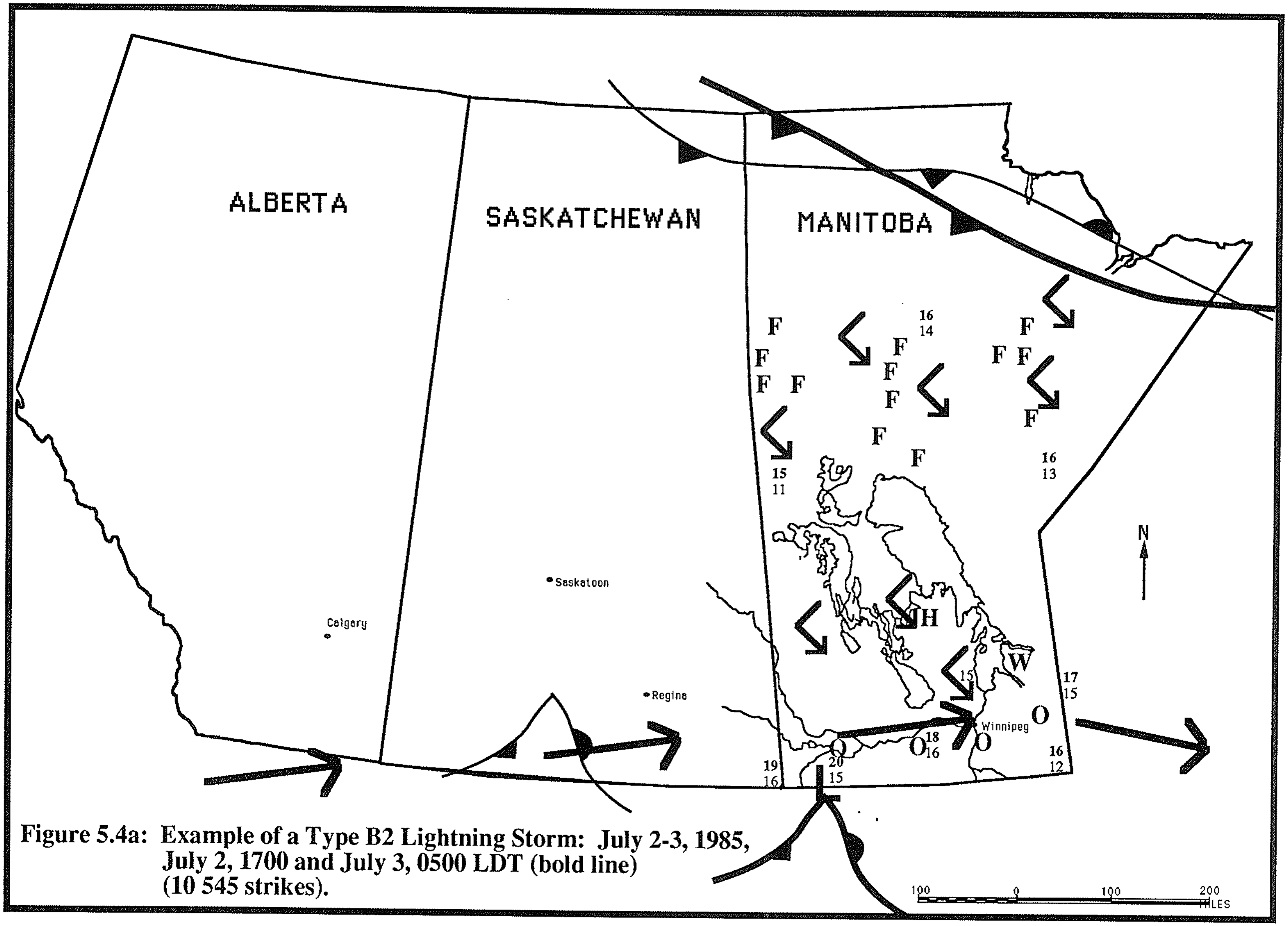


Figure 5.4a: Example of a Type B2 Lightning Storm: July 2-3, 1985, July 2, 1700 and July 3, 0500 LDT (bold line) (10 545 strikes).

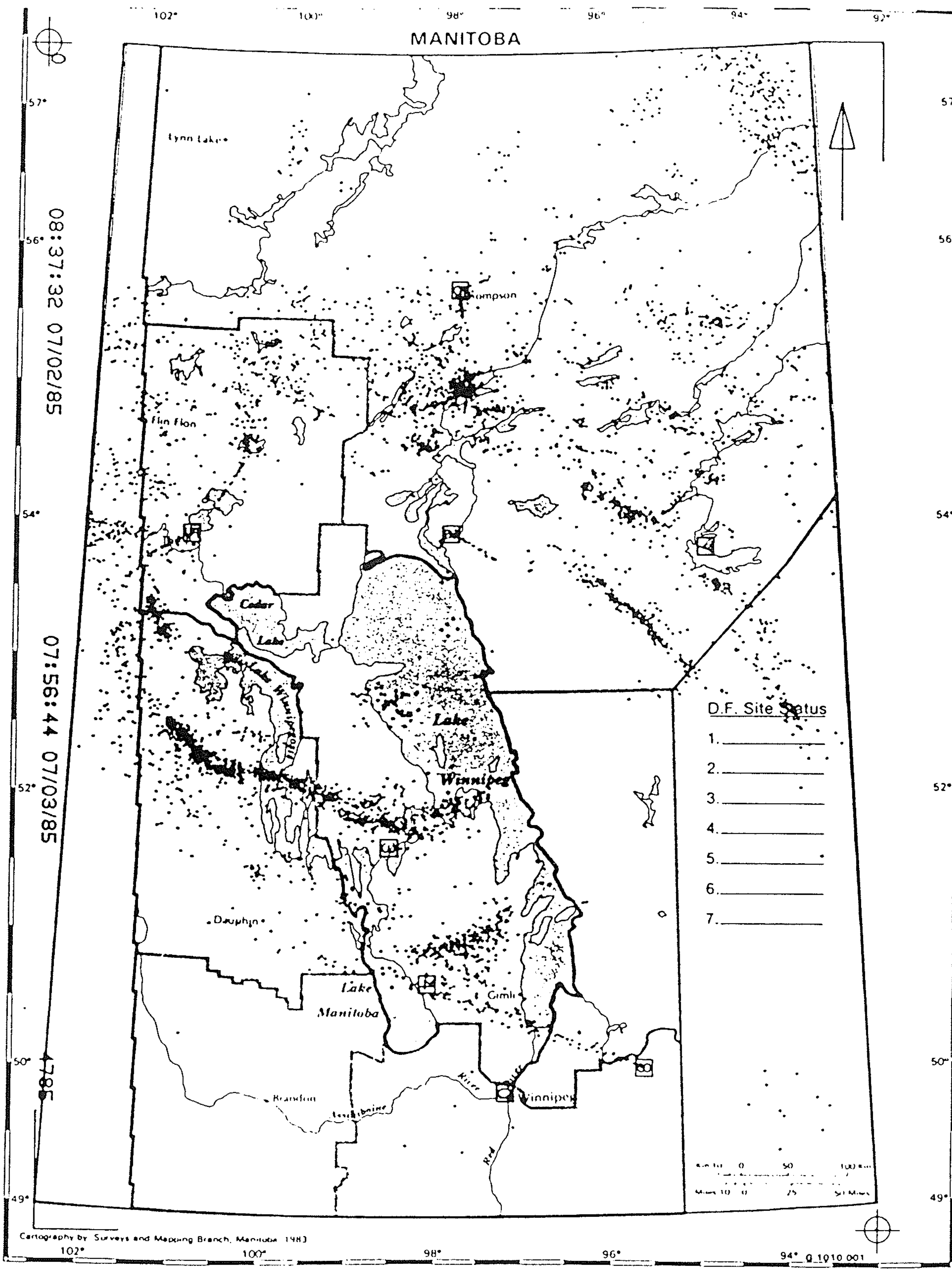


Figure 5.4b: Lightning Strike Distributions: July 2-3, 1985.

(July 2, 1700 to 2200 LDT). Strikes were found between two fronts. A well-developed frontal wave was found in the south and a cold front edge in the north part of Manitoba with strikes forming bands parallel to the more northerly cold front. Heaviest lightning occurred just north of the jet axis, parallel to it. Strike direction was from the northwest.

The greatest number of forest fires (15) and greatest area burned (over 12 000 Ha) of all case days were started by lightning strikes during this storm system, all of them in the Northern (West), Northern (East) and North Central regions. There were 34 reports of hydro disruptions, all in the south, with one 138 KV station in the southeast inoperable for 40 minutes. Moderate temperatures prevailed over the whole province and Tds were fairly high in the south. Strong winds and large hail occurred on the east side of Lake Winnipeg and in the Interlake during the early evening of July 2 between 1800 and 2000 LDT.

5.3.4: Type B3: August 19, 1986 (Figures 5.5a and b)

On August 19, 1986 most of the 7 919 strikes were primarily found in two areas: northeastern and southeastern Manitoba. Two frontal systems were present in north and south Manitoba, strikes concentrating between the two fronts. Storms in the southeast occurred during the morning with golf ball size hail recorded east of Lake Winnipeg at Victoria Beach. On the other hand, lightning storms in the northeast started during late afternoon, continuing until late night. In the south, as the well-developed frontal wave

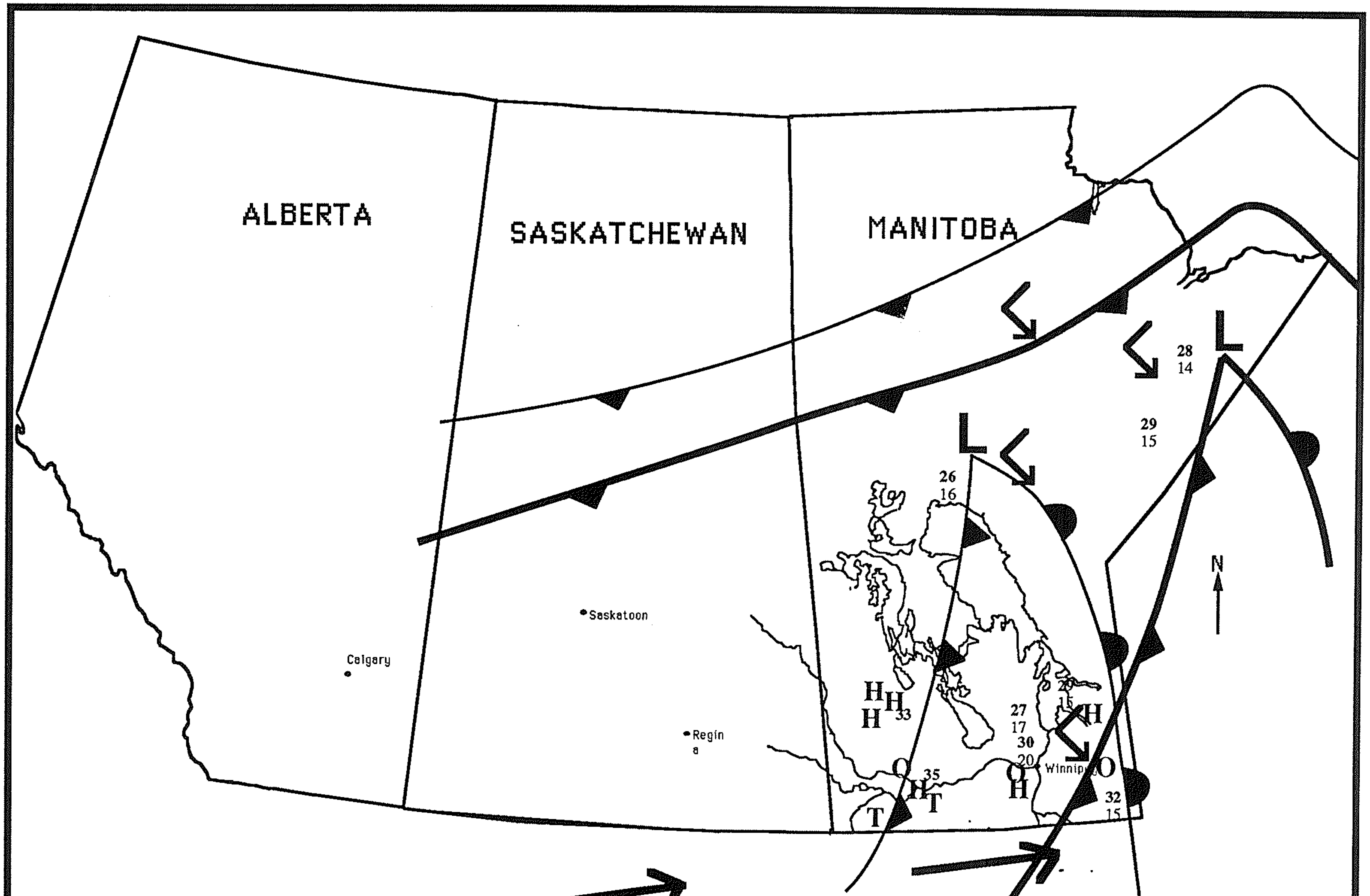


Figure 5.5a: Example of a Type B3 Lightning Storm: August 19, 1986, 1700 and 2300 LDT (bold line) (7 919 Strikes).

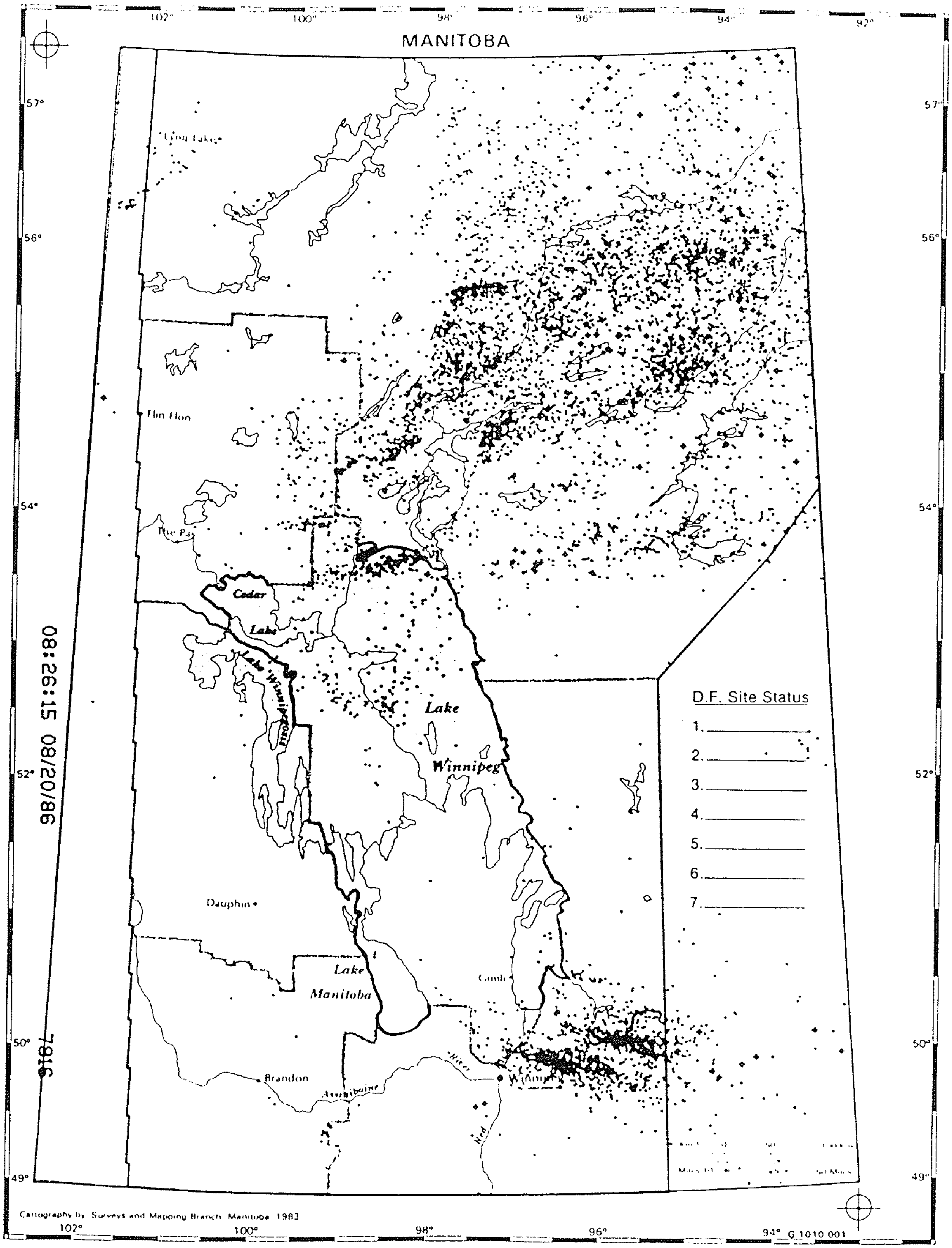


Figure 5.5b: Lightning Strike Distributions: August 19, 1986.

travelled northeastward, strikes were found ahead of the cold front, just north of and parallel to the jet axis. As the low moved becoming positioned just north of Lake Winnipeg at 1700 LDT, lightning storms developed around the low and slightly northeast of the apex. They appear oriented with and parallel to.the northern cold front. All strikes were north of the 250 mb axis.

Local incidents of large hail but almost no lightning activity were reported for the Dauphin, Brandon and Red River Valley areas. Two tornadoes touched down in the southwest during the early evening after a very hot day. Temperatures at Dauphin reached 32.9°C and 35.2°C at Brandon. High Tds occurred across the entire province, particularly in the northern half of Manitoba (19°C at Churchill, 18°C at Thompson and 16°C at Norway House). No forested areas, however, were damaged, partly because there was sufficient precipitation to suppress fires. Of the 39 lightning-caused power interruptions, most occurred in the southeast.

5.3.5 Type C2: August 7-8, 1986 (Figures 5.6a and b)

During this two day period, a west-east oriented cold front was advancing south across the province. On August 7, which had 2 842 strikes, the cold front was situated in northern Manitoba at around 55° N with all lightning strikes located south of the front boundary in the late afternoon and night. An intense low pressure cell was also covering the province. Most strikes occurred in the Interlake and North Central regions at around 1700 LDT, clustering over the north basin of Lake Winnipeg and between Lake Manitoba and

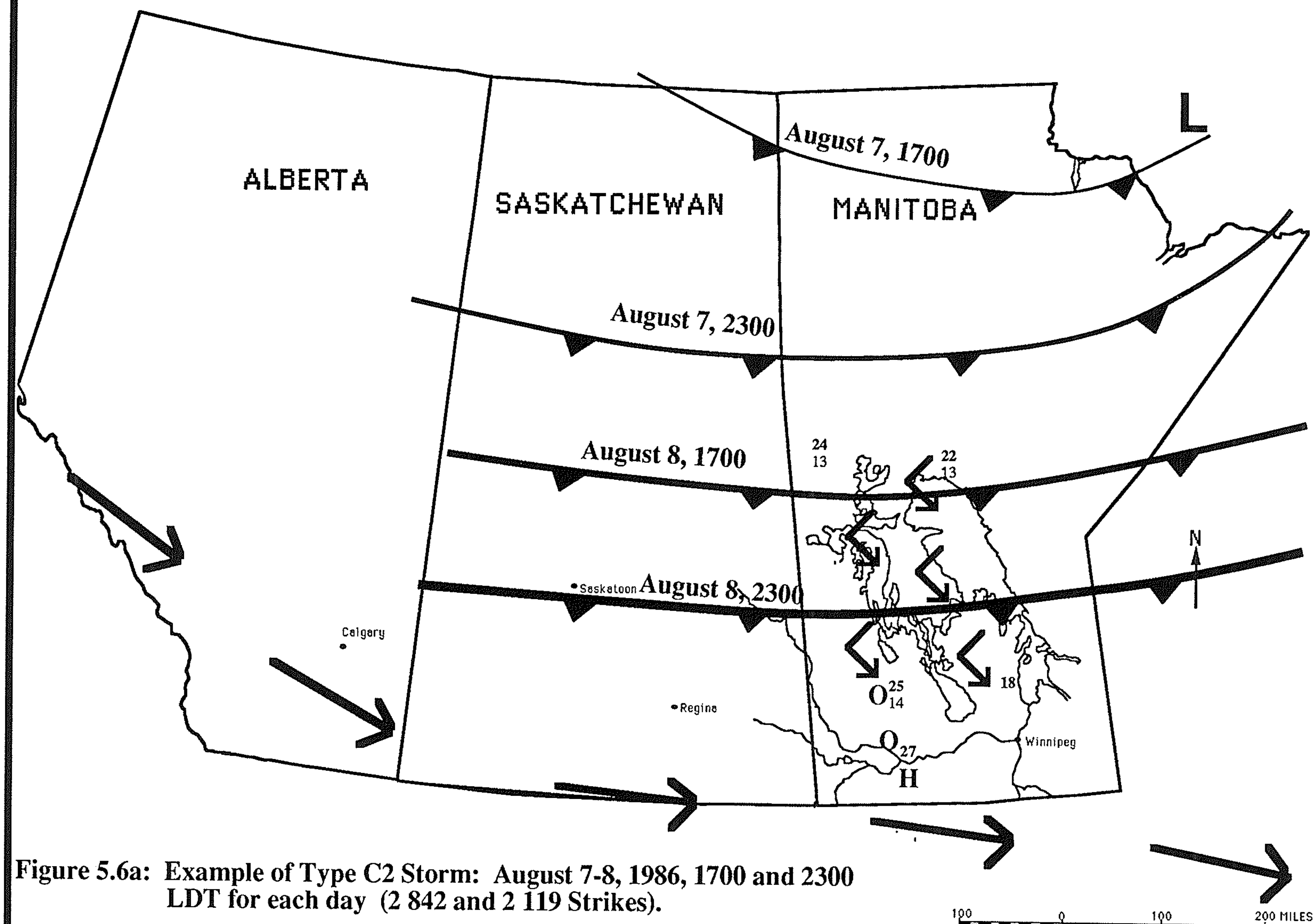


Figure 5.6a: Example of Type C2 Storm: August 7-8, 1986, 1700 and 2300 LDT for each day (2 842 and 2 119 Strikes).

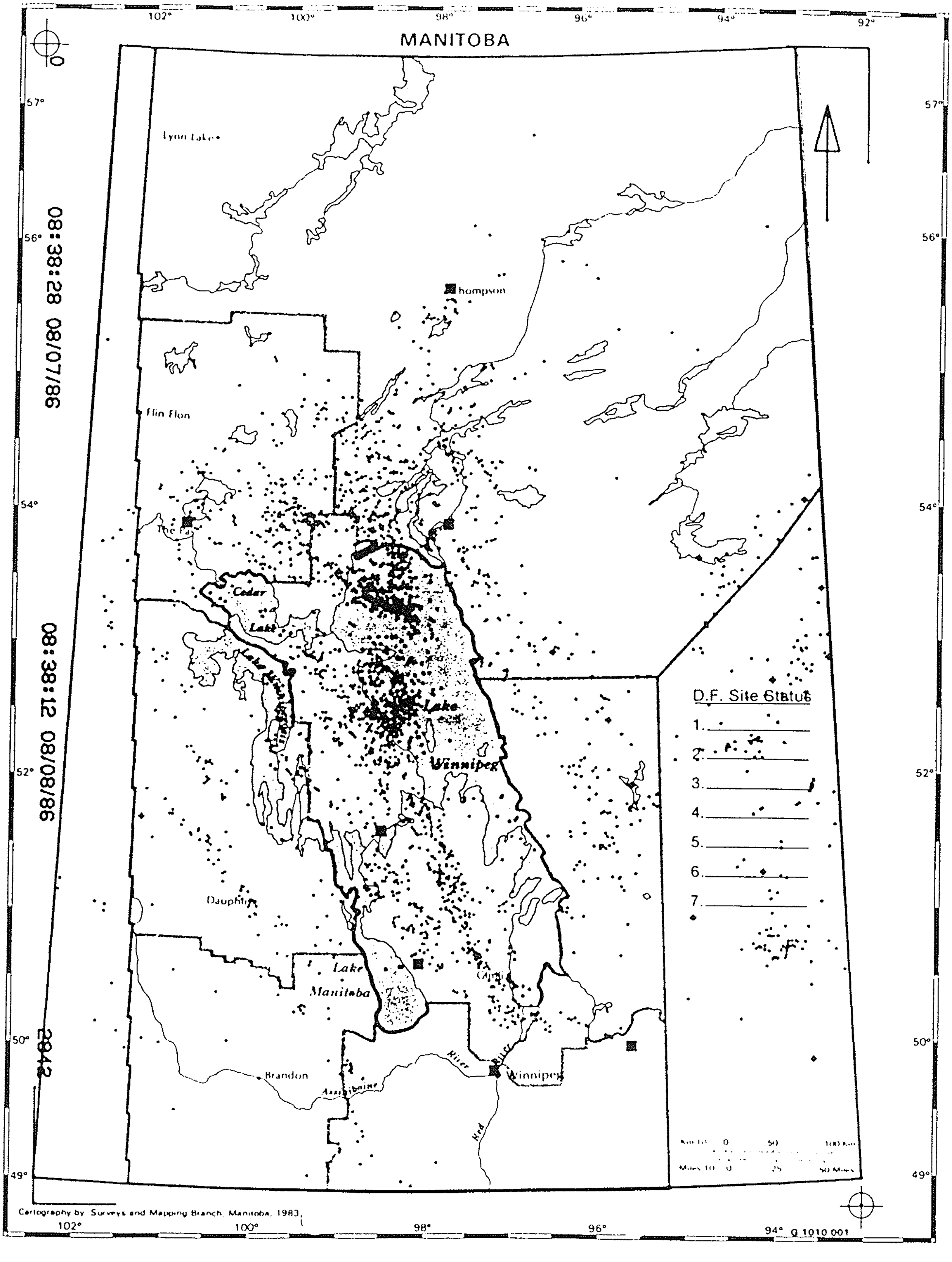


Figure 5.6b: Lightning Strike Distributions: August 7-8, 1986.

the south basin of Lake Winnipeg. The area of strikes was north of the 250 mb axis. Heavy precipitation in the Interlake and North Central regions probably helped with forest fire suppression as no fires were ignited. Four brief disruptions occurred and no severe weather was logged.

On the second day, August 8, there were slightly fewer strikes than on the previous day. By now, the cold front was positioned in a more southerly location, crossing the province at around 52° N. Strikes were still found north of the jet axis. Many strikes continued to occur in the Interlake but high concentrations were now also found in the two Western regions instead of the North Central region. As on the previous day, strikes fell south of the cold front and perpendicular to the cold front edge. Storms occurred in the late afternoon and again late at night. Forest fires did not occur but nine power interruptions and a localized incident of hail were recorded in the southwest.

Studying lightning distributions and associated synoptic features is another possible application of lightning detector data. Maps may eventually be produced which show ground lightning distributions and the typical circulation that caused the strike distributions. If various synoptic types are known to cause clusters of lightning activity in particular areas, then forecasts warning of possible lightning hazards can be issued. By examining synoptic patterns and lightning distributions, and also comparing them with forest fire or power interruption data, potential hazard areas in Manitoba can be identified.

CHAPTER 6

SUMMARY, CONCLUSION AND RECOMMENDATIONS

This study has utilized a recently available data source which provides direct information on cloud-to-ground lightning strikes for the province of Manitoba. The benefits and disadvantages of the measuring equipment were discussed. It was concluded that although there are some locational inaccuracies, these data do provide very useful information, especially in areas which are poorly covered, or not monitored at all, by the AES weather stations. Spatial and temporal distributions and variations of lightning strikes were investigated using data from the 1985 season. Lightning patterns were then compared with thunderstorm records kept by the AES. Examples of applications for lightning detector data were presented in conjunction with forest fire reports, power disruption logs and synoptic weather features.

6.1 SUMMARY AND CONCLUSION

Cloud-to-ground lightning strike occurrences varied throughout the province. Three general areas of high lightning activity were identified: west-central Manitoba, the southeast part of the province and in the Interlake. Two of these areas were located mainly over the more rugged shield terrain of the province. The Interlake also has a relatively rugged and forested terrain.

These regions also experienced a high frequency of strikes during the storms selected for the case studies. Visual inspection of hard-copy lightning maps, indicated that strikes in the Interlake and western part of the province showed no preference for land or water. Over both major lakes, high strike concentrations were common during intense lightning storms, with greater frequencies sometimes occurring over water rather than land. These lakes, then, probably do not add any stabilizing influence and possibly enhance the electrical nature of thunderstorms. Strike densities were greatest in west-central Manitoba, the Western 2 (North) region and in southeastern Manitoba.

July recorded most strikes, followed by August and June. These three months accounted for 88.5% of all strikes recorded from May 23 to October 3, 1985. August, however, experienced most days with lightning, followed by July and then September. This order was different from that of recorded thunderstorm days which were greatest in July, August and June. Lightning days were consistently commoner than thunderstorm days for the province. When lightning days were compared with thunderstorm days on a smaller scale at 11 climate stations, lightning days were still generally higher than thunderstorm days. Discrepancies could result because of poor coverage by weather stations, thunderstorms producing only intra-cloud lightning or strikes being located just beyond audible thunder range of a climate station. DFs also have coverage limitations and could experience mechanical difficulties, resulting in locational errors.

A diurnal frequency distribution of strikes followed previously identified thunderstorm patterns. Southern Manitoba, south of 54°N received about 65.0% of the 1985 total of 67 912 strikes at night. The northern half recorded almost all strikes in the afternoon and early evening unlike the south which had relatively high strike numbers throughout the entire 24 hour period. In the northern half, some activity begins in late morning, expanding eastward as the afternoon progresses and decreasing very rapidly after an afternoon peak. In the south, lightning was found during late morning in the east, this eastern activity joined by western activity in the afternoon. By early evening, values decreased in the east, still remaining high in the west and finally reaching peak levels at night. After midnight, activity decreased in the west but not in south central Manitoba, with high values shifting eastward through the night.

The distributions of lightning-caused forest fires and power disruptions, as well as synoptic patterns associated with 31 selected case study storms were discussed as examples of possible applications of lightning detector data.

The total number of lightning-caused forest fires in 1985 was 136 and over 98 500 Ha were burned. This was almost double the 1986 fire numbers (73) and more than double the area destroyed (38 200 Ha). Although 1985 recorded fewer total strikes than 1986, more forest fires were ignited by lightning because of generally drier conditions which created fire-hazard conditions. The East Central, Southeast and Northern (West) and regions experienced most fires. The Southeast region was the only one that had a high lightning strike frequency in both years.

In contrast, 1985 recorded fewer lightning-caused hydro interruptions than 1986. Outages were concentrated in southern Manitoba as expected because of the greater number of thunderstorms in that area and high density of transmission lines. After the South Central and Southwest regions, the Southeast and Interlake regions logged the next two highest outage densities, these being two of the regions identified as high strike density locations.

A small number of very active storms accounted for the majority of the strikes. These were classified according to their synoptic conditions and case studies of each class were examined in detail. This classification was based on two circulation features: surface fronts and upper level jet directions. Various characteristics, such as the direction and location of strikes, weather conditions and other associated phenomena , for example, forest fires and power disruptions, were outlined. In the 31 sample storms, Type A3 was the most common storm type, followed by Type A1. These two types had similar surface characteristics, namely, an advancing north-south oriented cold front, with storms occurring ahead of the cold front. The upper level jet came predominantly from the southwest or west. Several characteristics were examined in each category but no factor could be identified as primarily dominant in producing particular storms. A larger sample size would be necessary for this purpose.

Areas of high lightning activity for Type A storms included the Western 1 (South), Southeast and Interlake regions, while most Type B storms occurred in the Interlake, Western 2 (North), and East Central regions. Lightning generally concentrated near the cyclone wave apex and south of it. Type A storms produced most forest fires but the fires associated with fewer Type B storms burned a much larger area. Actually, only one day caused most of the damage so this result for Type B may not be really indicative of long-term conditions. Types B3 and A3 recorded highest and second highest number, respectively, of power disruptions per storm. However, B3 storms had only one day with an extreme number of disruptions perhaps giving undue weight to the B3 type of events. Type A3 accounted for 61.7% of severe weather events, which included damaging winds, hail, heavy rain or tornadoes, all occurring in the southern half of the province. Strong wind gusts were the most common element of the severe weather with hail second.

This thesis has discussed the spatial, diurnal and seasonal strike distributions in Manitoba. Recently available lightning strike data were compared with familiar meteorological thunderstorm data, showing similarities at some locations and differences at others. These results indicate that the lightning data are especially valuable for regions not well represented by the AES observational data. From the distributions, three areas of Manitoba were identified as experiencing high strike densities, these areas also occurring where there is relatively sparse weather station coverage.

Conceivably, lightning DF data could be used in conjunction with standard thunderstorm recording methods in order to verify and add to thunderstorm climatology knowledge. Combining all available thunderstorm and lightning data will provide a better understanding of these phenomena and their relationships with other parameters. Greater DF coverage supplying the most up-to-date reports of strikes will facilitate the efficient co-ordination and dispatch of suppression or repair crews to fight fires and repair power lines. Continued studies of lightning behaviour and associated synoptic features could disclose identifiable weather patterns responsible for various lightning distributions and densities.

Locational information of lightning strikes will improve the lightning/thunderstorm climatology for much of Manitoba. A damage-based lightning climatology was previously available. This thesis includes a new lightning climatology for the province using a data source that can include almost all lightning strikes, not just those that caused visible damage. Actual cloud-to-ground strikes were mapped and graphed to show distributions and variations, giving an indication of how common and widespread this phenomenon can be over Manitoba.

6.2 RECOMMENDATIONS

This study has used a new source of information to examine lightning strikes in Manitoba. However, this is a preliminary study of the data source and much work can yet be accomplished by more detailed research. Attention should focus on particular areas of the province, such as the forests, where DF data are best. Lightning strike distributions could be viewed to help identify forest fire hazard regions. On the other hand, using additional years of detector data would improve the provincial lightning climatology presented here. On both scales, strikes and their relationship with such phenomena as major and minor topographic features, lakes, urbanization and synoptic variables, would be very useful in preparing a lightning hazard map for Manitoba. Individual lightning storms could be studied to see how strikes develop and abate through time as a storm system moves. Using a large sample of lightning storms would yield more information about what kinds of weather patterns are responsible for thunderstorms producing differing amounts of cloud-to-ground strikes.

Movements of lightning storms across Manitoba and associated distributions of cloud-to-ground strikes and lightning-caused forest fires is another area requiring more work. By noting spatial relationships between synoptic weather patterns and the distribution of strikes, predictions may be made about the areas most susceptible to lightning-ignited forest fires and about the locations where power outages are most likely to occur.

If detector range is increased in order to adequately monitor southern Manitoba, the potential effects of such features as the city of Winnipeg, the Manitoba Escarpment or Lakes Winnipeg and Manitoba on southern lightning strikes could be investigated. The addition of a northern Ontario DF station to the Manitoba network would possibly eliminate some of the baseline errors in southeastern Manitoba. Also, Manitoba has pockets of rich mineral deposits and the potential effects of metallic ore concentration in attracting cloud-to-ground strikes can be studied.

While other studies using DF data have been undertaken, especially in the US, this was the first attempt to employ Manitoba's DF information for a climatology study. In the process, some problems were discovered. Because DFs monitor vast, uninhabited parts of Manitoba, compilation and dissemination of this data has a great potential to provide more accurate and complete coverage of severe weather in the province. Reliance on human observation of thunderstorms leaves much of Manitoba unmonitored. Before DFs can monitor the whole province, some limitations that presently exist must be mitigated or eliminated.

Additional detectors would have to be installed in order to properly monitor southern Manitoba. Storage of lightning detector data could also be improved. Although the data are readily available, in their present form, information is stored on cassette tapes which can only be read using a special recorder that is part of the LLP detector hardware. These tapes were sent to the LLP company in Tucson, Arizona in order to be converted into a format that was compatible with computers in Manitoba. Furthermore, the cassette has to be manually reset each day. An improved archiving system should eventually be implemented, thus improving the continuity of the data. Cooperation between the AES and Fire Management Division would prove to be useful so lightning strike and weather information are integrated, thereby imparting a holistic picture of this phenomenon.

Other information recorded by the detection network, like amplitude of the return stroke, number of return strokes per flash and discharge polarity deserve study. Does the number of return strokes show any spatial or temporal pattern? Do topographic features have any effect on the frequency of return strokes? Is polarity effected by topography? What are the differences, if any, between positive and negative discharges, in relation to storm intensity, synoptic features or forest fire ignition? These are examples of questions that may be addressed by DF data.

Regional differences and similarities of lightning strike distributions and intensities have various implications for thunderstorm studies. Observing flash frequency during a storm could indicate the developmental progress of a thunderstorm, possibly assisting in forecasting severe weather. Some distinct spatial and diurnal lightning distributions could be identified, especially in localized areas, in order to provide valuable estimates of the most probable time for the beginning and ending of thunderstorm activity (Crozier et al., 1988). Lightning strike densities are useful for determining ground flash hazard areas. Densities calculated during the entire thunderstorm season and also on a diurnal schedule might show variations in hazard areas through time. This information would be useful for numerous planning purposes.

A number of preliminary but very useful findings revealed the great potential of lightning strike data. As technology continues to develop in the lightning detection field and problems concerning its use are resolved, this "unique source of accurate and timely information on the presence or absence, location, intensity and movement of lightning storms " over any area will become an essential component in "management of lightning sensitive resources or warnings of lightning and thunderstorm hazards" (LLP, Inc., 1984).

APPENDIX 1
DEFINITIONS OF LIGHTNING FORMS

A common lightning form, the cloud-to-ground *forked lightning* discharge occurs between the cloud base and earth's surface appearing as a jagged path of light with numerous branches extending outward into the air from the main branch. Another cloud-to-ground discharge is *streaked lightning*, similar in development to *forked lightning* except that *streaked lightning* is visible as a single pathway with no branching.

Ribbon lightning, a rarely seen form, occurs if very strong winds displace the conducting channel downwind so that a lightning flash would appear as a wide, ribbed band rather than a typical, relatively narrow solid flash.

Sheet lightning from a distant thunderstorm, but from a storm near enough so that thunder is heard, lights up a part of the cloud while *heat lightning* is a faint lighting of the sky from an even more distant thunderstorm, where thunder cannot be heard.

If the lightning conducting channel is built horizontally rather than vertically, the cloud discharges into the air. A *bolt from the blue*, a lightning discharge appearing to come from clear sky is initiated from this *air discharge* which can travel horizontally across the sky as far as 20 kilometres.

The rarest form of lightning, and least understood, *ball lightning,* as its name suggests comes in the shape of a ball which has been reported to 'roll' or 'float' over the ground.

When the tops of tall objects (towers or mountain peaks, for example) emit a glow "because of the positive charges that remain as the negative charges drain away when a thunderstorm moves over head" (Eagleman, 1983), this is termed *St. Elmo's Fire* , yet another form of storm electricity.

APPENDIX 2

Key to Abbreviations of Regions

Abbreviation	Region
E.Cen	East Central
Int	Interlake
N.Cen	North Central
Nor(E)	Northern (East)
Nor(W)	Northern (West)
S.Cen	South Central
SE	Southeast
SW	Southwest
West1	Western1 (South)
West2	Western2 (North)

APPENDIX 3a

Type A Case Study Storms and the Three Regions with Most Lightning Activity

	Region with Lightning Activity		
Storm Type A	Most Active	Second-most Active	Third-most Active
1985			
July 12	Western2(N)	Western1(S)	Northern(W)
23	Southeast	East Central	Interlake
27	Western1(S)	Interlake	East Central.
Aug 5	Northern(W)	Western2(N)	Western1(S)
26	Interlake	Northern(W)	Western1(S)
Sept 5	Southeast	Western1(S)	Interlake
1986			
June 11	Western2(N)	Western1(S)	Interlake
19	South Central	Southwest	Interlake
25	Interlake	Southwest	South Central
July 3	Southwest	South Central	Southeast
5	South Central	Southeast	Southwest
22	Northern(W)	Southwest	Western1(S)
23	East Central	North Central	Western2(N)
25	Western1(S)	Southwest	North Central
28	Southeast	East Central	Interlake
29	Interlake	Western1(S)	Western2(N)
Aug 13	Western1(S)	East Central	Northern(E)
14	Northern(W)	Southeast	Northern(E)
19	Northern(E)	Southeast	East Central

APPENDIX 3b

Type B Case Study Storms and the Three Regions with Most Lightning Activity

Storm Type B	Region with Lightning Activity: Most Active	Second-most Active	Third-most Active
1985			
June 20-21	Western2(N)	Interlake	Western1(S)
July 2-3	Interlake	Western2(N)	East Central
15	Western2(N)	Northern(W)	North Central
Aug 3	Southeast	Southwest	Western1(S)
31	East Central	Southeast	Western2(N)
1986			
June 21	East Central	Interlake	North Central
24	Western2(N)	Interlake	Western1(S)
July 17	Southeast	Interlake	South Central
Aug 6	Interlake	East Central	Western1(S)

APPENDIX 4

Number of Forest Fires for Case Study Days and Area Burned by Storm Type

	Forest Fires		
	Region	Frequency	Hectares Burned
Storm Type A1			
1985			
July 27	Interlake	1	240 Ha
Aug 5	Western2(N)	7	49
26	Northern(W)	3	45
	East Central	2	35
1986			
June 25	Southeast	1	1
July 22	East Central	1	10
	Southeast	1	12
Aug 13	East Central	1	20
Storm Type A3			
1985			
July 12	Northern(W)	1	20
	Southeast	2	2
1986			
July 3	Southeast	2	4
	East Central	2	101
5	South Central	1	1
23	Interlake	1	61
	Southeast	5	21
	East Central	8	1 616
	North Central	2	30
28	East Central	1	1

	Forest Fires Region	Frequency	Hectares Burned
Storm Type B1			
1986			
June 24	Southeast	1	1
Storm Type B2			
1985			
July 2-3	Northern(E)	3	2 630
	Northern(W)	8	9 620
	North Central	2	45
	Western2(N)	2	27
15	Northern(W)	1	4
Storm Type B3			
1985			
Aug 3	Northern(E)	1	1
	East Central	1	25
	Southeast	1	1
1986			
June 21	East Central	1	1
July 17	North Central	1	28
Storm Type D2			
1986			
Aug 3	Northern(W)	2	54
	Southeast	1	5

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