Summer Convection and Lightning over the Mackenzie River Basin and their Impacts during 1994 and 1995

B. Kochtubajda[1*], R. E. Stewart[2], J. R. Gyakum[3] and M. D. Flannigan[4]

[1]*Meteorological Service of Canada, Prairie and Northern Region,*
Edmonton AB T6B 2X3
[2]*Meteorological Service of Canada, Climate Research Branch,*
Downsview ON
[3]*McGill University, Department of Atmospheric and Oceanographic Sciences,*
Montreal QC
[4]*Canadian Forest Service, Northern Forestry Centre,*
Edmonton AB

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ABSTRACT *Lightning activity over the Mackenzie basin has been examined for the summers of 1994 and 1995. In recent years, the lightning network operating in the Northwest Territories has detected an average of 118 K strikes per season. Positive lightning strikes (defined as lightning discharges lowering positive charge to the earth) typically comprise 12% of the total. The lightning activity during 1994 was approximately 20% below normal, while in 1995, it was 53% below normal. However, the fraction of positive lightning strikes was 25.6% during 1995. The lightning was linked to synoptic conditions favouring severe storm development, especially those tied to the diurnal cycle. As a consequence of the lightning, as well as the very dry surface conditions, record forest areas were burned. In the Northwest Territories alone, forest fires burned 3 Mha in 1994 and 2.8 Mha in 1995.*

RÉSUMÉ *[Traduit par la rédaction] L'activité de foudroiement au-dessus du bassin du Mackenzie a été étudiée pour les étés 1994 et 1995. Au cours des dernières années, le réseau de détection de la foudre en exploitation dans les Territoires du Nord-Ouest a détecté en moyenne 118 K foudroiements par saison. Les foudroiements positifs (définis comme des décharges électriques qui abaissent la charge positive au sol) contribuent normalement à 12% du total. L'activité de foudroiement en 1994 a été d'environ 20% inférieure à la normale, tandis qu'en 1995, elle a été de 53% inférieure à la normale. Toutefois, en 1995, le pourcentage de foudroiements positifs a été de 25,6%. La foudre avait un lien avec les conditions synoptiques qui favorisaient le développement de tempêtes violentes, principalement celles associées au cycle diurne. Par suite du foudroiement ainsi que des conditions très arides à la surface, des superficies forestières record furent brûlées. Dans les seuls Territoires du Nord-Ouest, les feux de forêt ont brûlé 3 Mha en 1994 et 2,8 Mha en 1995.*

1 Introduction

Deep convection is a common feature during the summer months over most areas of the Mackenzie River Basin. In addition to producing beneficial rainfall, this convection is linked with the vertical transport of moisture and momentum through the troposphere and it can also produce flooding events. The convection, therefore, plays a crucial role in the water cycle of the region. Associated lightning activity can also trigger major forest fires. However, studies of deep convection over this region have been limited by the scarcity of surface-based weather observing sites. In fact, we are not aware of any studies in the scientific literature addressing this issue throughout the Mackenzie basin.

The Mackenzie River is the largest North American source of fresh water for the Arctic Ocean, ranking tenth in the world by drainage area. The drainage basin covers approximately 1.8 million km^2 or about 20% of Canada's landmass, and is characterized by mountainous regions in the west, lakes and wetlands on the Interior Plain, rocky Canadian Shield in the east, arctic tundra in the north and boreal forest and agricultural lands in the south (Fig. 1).

Studies of deep convection can now take advantage of the automated networks that have been established within the basin over the last few years to detect cloud-to-ground lightning strikes. Information from these networks can provide a good indication of convective activity. Each cloud-to-ground flash detected by the networks is composed of a series of events: a cumulonimbus cloud becomes predominantly positively charged at the top of the cloud and negatively charged

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*Corresponding author's e-mail: bob.kochtubajda@ec.gc.ca

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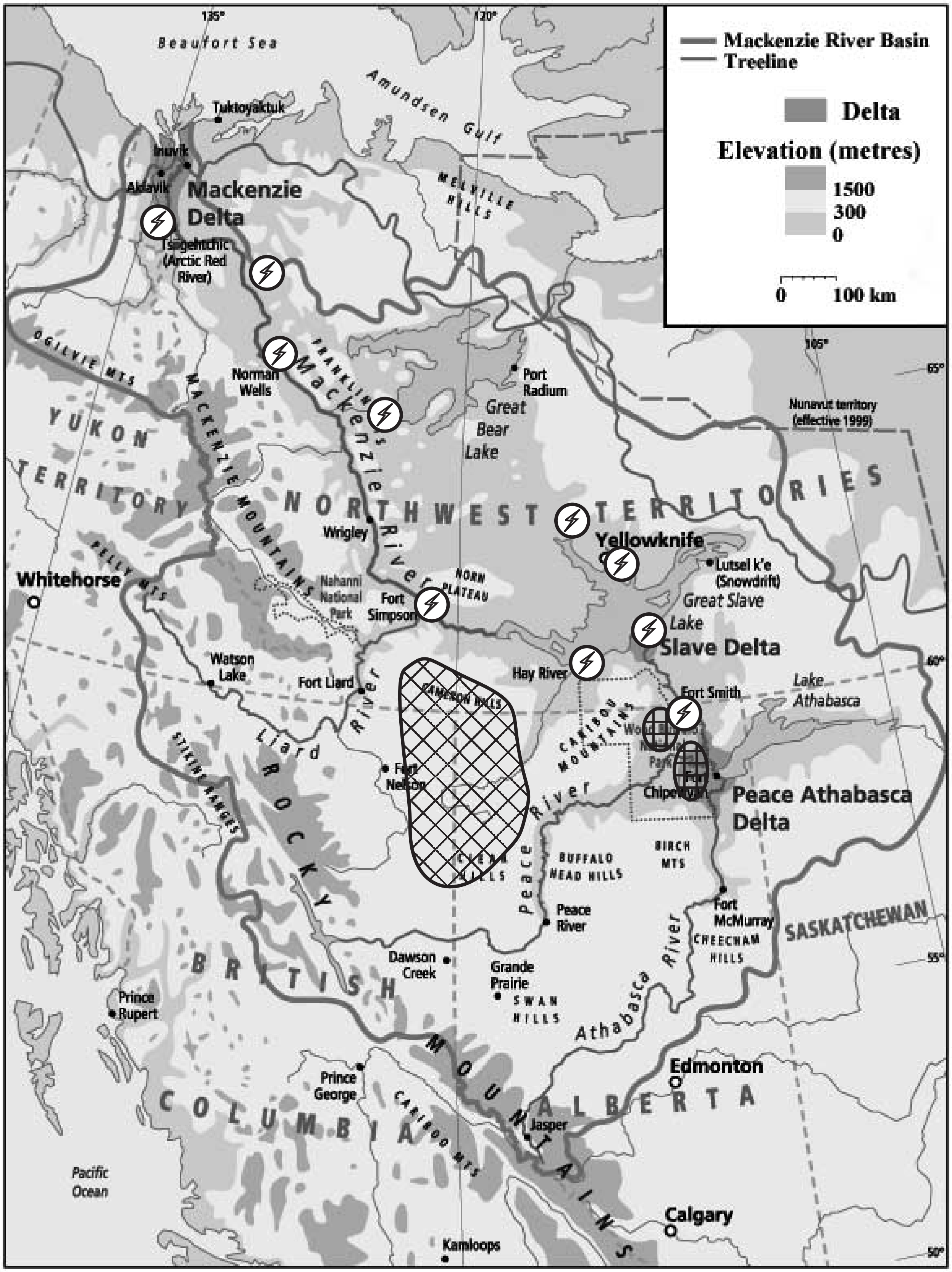


Fig. 1 The Mackenzie River basin and some of its features and population centres. Areas of maximum lightning activity in 1994 and 1995 are highlighted. The NWT lightning detection network operating in the basin during the 1994 and 1995 seasons is shown. This map was adapted from one produced by E. Leinberger for the Mackenzie Basin Impact Study (Cohen, 1997).

near cloud base. A flash begins as a “step leader” that “jumps” about 50 m at a time toward the ground. As the step leader approaches the surface, “streamers” moving up from a tree or any other protuberance, travel upward and an electrical channel is formed when the two meet. A series of electrical current surges, referred to as return strokes, follow. Typically, 2–4 return strokes make up a flash. Usually they lower negative charge to the surface and are referred to as negative lightning flashes. Sometimes, however, flashes lower positive charge to the surface. The typical flash carries a peak current of 30 kA. Additional information can be found in Uman (1984).

Lightning detection networks have been used to produce lightning climatologies and to infer characteristics of convection in other regions. For example, Orville (1994) and Reap (1991) produced such climatologies for the continental United States and Alaska, respectively. Finke and Hauf (1996) produced a climatology for Germany. Lightning data have also been used to estimate convective rainfall (Tapia and Smith, 1998) and to provide useful precursors of flash flood events over rugged areas (Holle and Bennett, 1997).

Several Canadian studies of lightning have been published. Hanuta and LaDochy (1989) used a lightning detection network to examine the thunderstorm climatology of Manitoba. In addition, climatologies have been generated for southern Ontario (Crozier et al., 1988), northern Ontario (Flannigan and Wotton, 1991), the southern Great Lakes area (Clodman and Chisholm, 1996), mid- to northern Saskatchewan (Li et al., 1997), and the subalpine and boreal forest regions of Alberta and Saskatchewan (Nash and Johnson, 1996).

There have also been some recent studies concerned with the global distribution of lightning (Mackerras and Darveniza, 1994; Mackerras et al., 1998). From this large-scale perspective, estimates have been made of the latitudinal variation of lightning including its diurnal tendencies. Global distributions of lightning have also been derived from satellite observations (Christian and Latham, 1998). None of this work has been directly applied to the Mackenzie basin, but the results from these studies indicate that this region experiences a relatively large amount of lightning, given its high latitude location.

It is, therefore, apparent that fundamental issues need to be addressed concerning lightning over the Mackenzie basin. These include determining typical and unusual lightning patterns over this region and gaining an understanding of the processes responsible for them. It is also critical to improve our appreciation of the impacts of this lightning on, for example, forest fire ignitions. The impact of forest fires in this region can have consequences far beyond the Mackenzie basin. For example, such fires have been shown to influence pollutant levels over the United States (Wotawa and Trainer, 2000). The emissions from the fires during the summer of 1995 were the largest sources of carbon monoxide and ozone over the south-eastern and eastern United States.

The objective of this study is to advance our understanding of the nature of lightning and convective activity over the Mackenzie basin during the summers of 1994 and 1995 through an examination of their spatial and temporal distributions, their relation to atmospheric and surface forcing, and their relation to forest fires. The paper is organized in the following manner. The data used in the study are described in Section 2; Section 3 summarizes the dominant weather features during both summers; Section 4 presents the lightning characteristics during both summers; Section 5 examines the forest fire activity within the Mackenzie basin; and Section 6 presents synoptic scale features associated with several lightning events. Conclusions are presented in Section 7.

2 Data

The study used a variety of data sources. These include the archived lightning strike data from the Northwest Territories government; lightning fire data from the Canadian Forest Service fire database and the provincial and territorial fire databases; climate (synoptic and sounding) data from the Environment Canada databases; and the historical gridded data from the National Centers for Environmental Prediction (NCEP).

A lightning detection network (Krider et al., 1980) has been established over the Northwest Territories to detect the occurrence of lightning strikes in the northern portions of the Mackenzie basin. The network only operates during the convective season between May and September. During the 1994–95 water year, there were 10 direction-finder stations distributed within the northern portion of the basin (Fig. 1), capable of detecting lightning over approximately 70% of the area. The network senses the electromagnetic fields radiated from cloud-to-ground lightning flashes and the time and location are determined by triangulating information from the stations. The systems are also able to differentiate between negative and positive charges. There are varying degrees of uncertainty associated with the location accuracy of the lightning data and the detection efficiency of the network.

Accuracy of the triangulated location is dependent on the distance between the direction finder and the lightning discharge as well as on the limitations of the direction finder site (e.g., signal attenuation by the local terrain). In Alberta, Nimchuk (1989) reported errors of 3–10 km in the location of the lightning position within the highest density area of the network. At the periphery, where the network was less dense, location errors of 12–22 km were found. The detection efficiency, defined as the percentage of the total number of cloud-to-ground flashes detected, is a function of range and sensor performance (Mach et al., 1986). The studies in Alberta and British Columbia reported detection efficiencies of approximately 70% within a range of 300 km (Nimchuk, 1989; Gilbert et al., 1987). The Northwest Territories lightning network is expected to have similar uncertainties in the location errors and detection efficiency (Lanoville, personal communication, 2000). In this study, the data were not corrected for detection efficiency.

Use is made of the Canadian Forest Service’s national fire database. The records, provided by the provincial and territo-

TABLE 1. Monthly distribution of lightning activity over the northern portion of the Mackenzie River Basin during 1994–95.

	1994					1995					Season	
	May	June	July	Aug	Sep	May	June	July	Aug	Sep	1994	1995
Negative strikes	1,522	19,878	40,096	20,232	913	378	18,577	15,386	6,329	750	82,641	41,420
% total	74.8	87.5	91.5	83.1	75.4	64.8	80.5	70.8	68	78.4	87.8	74.4
Positive strikes	513	2,838	3,707	4,105	298	205	4,494	6,340	2,983	207	11,461	14,229
% total	25.2	12.5	8.5	16.9	24.6	35.2	19.5	29.2	32	21.6	12.2	25.6
Total strikes	2,035	22,716	43,803	24,337	1,211	583	23,071	21,726	9,312	957	94,102	55,649
Number of Days	17	28	26	31	11	2	30	31	30	12	113	105
Days > 500 strikes	0	14	16	12	1	0	13	11	6	1	43	31
Days > 2000 strikes	0	2	6	4	0	0	4	3	0	0	12	7

TABLE 2. Summary of lightning activity over the northern portion of the Mackenzie River basin for the period 1994–1999. Data are courtesy of the Forest Management Division of the Government of the Northwest Territories.

Year	Total Strikes	Positive Strikes	% Positive
1994	94,102	11,461	12.2
1995	55,649	14,229	25.6
1996	119,267	13,763	11.5
1997	155,219	15,032	9.7
1998	172,893	18,147	10.5
1999	111,971	13,857	12.4
mean (1994–1999)	118,184	14,415	12.2

rial governments, identify the date of the fire, the province where the fire occurred, a unique fire identification number, the fire location, the start and detect dates, the cause of the fire (human, lightning, or unknown), and the fire size.

The study also utilizes information from Environment Canada's operational networks. As shown in Stewart et al. (1998), there are a number of surface and sounding sites located within and near the basin. Although limited, these provide unique, critical information.

3 Weather summary for 1994 and 1995

Cao et al. (this issue), Louie et al. (this issue) and Stewart et al. (this issue) discuss various aspects of the weather conditions during 1994 and 1995. In general, they found that the summer of 1994 and the spring and summer of 1995 were drier than normal. This was associated with the persistence of surface high pressure conditions in and near the Mackenzie basin. Such situations led, for example, to periods of record-low values of surface humidity during the summer of 1995, above normal cloud base heights, below normal precipitation, and record-low lake levels and discharge values. Nonetheless, surface temperatures were, in general, above normal during the two summers.

Large-scale conditions were then quite unusual during 1994 and 1995. As will be shown, they were also quite consistent with the development of deep convective activity, lightning, and forest fires.

4 Lightning climatology for 1994–95

In this section, lightning characteristics are described using the available information described in Section 2. The monthly lightning strike variations for two seasons (14 May – 18 September 1994 and 30 May – 29 September 1995) are summarized in Table 1.

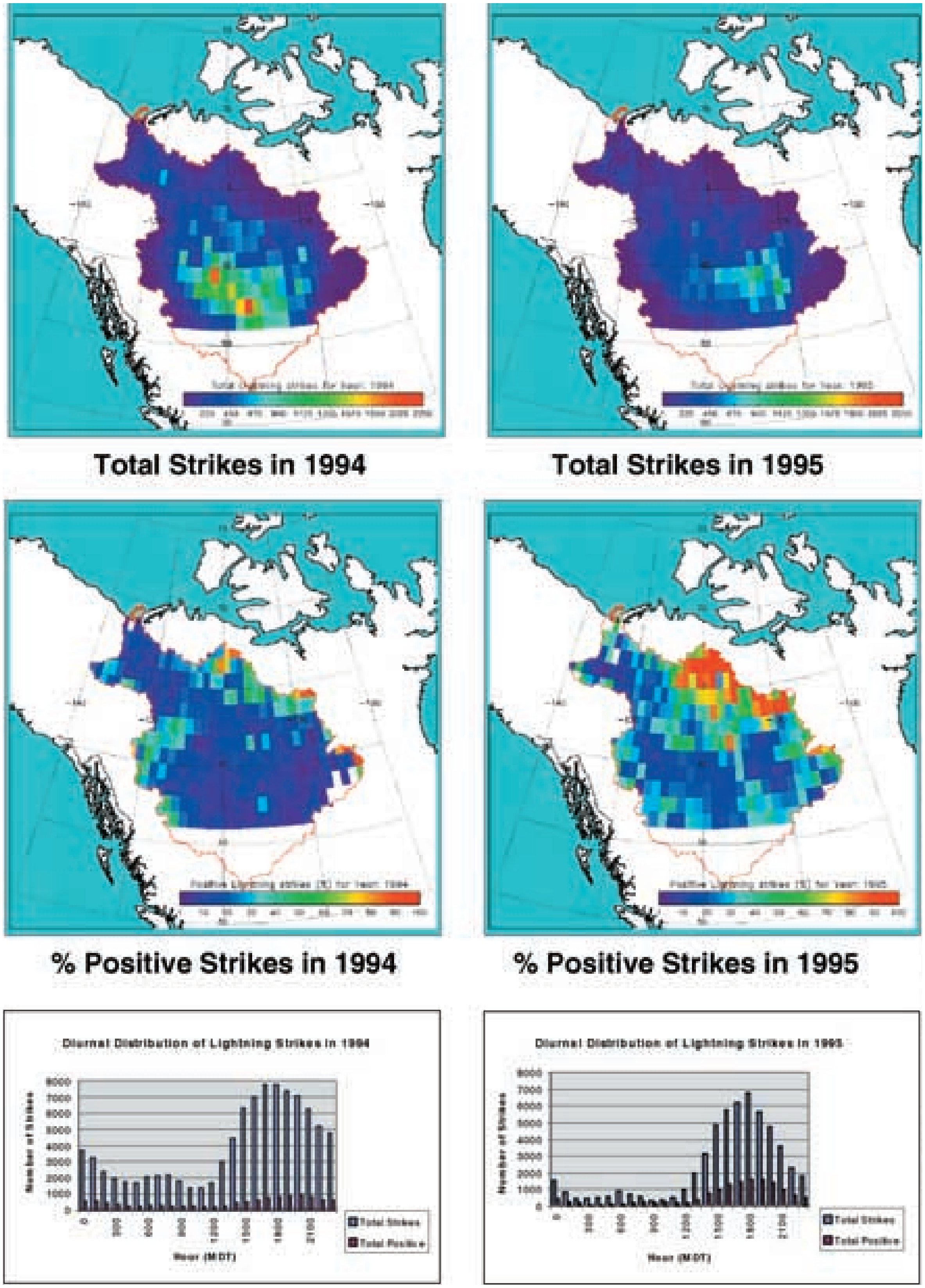
Approximately 94,000 flashes were recorded on 113 days (88% of the available time) in 1994, and 56,000 flashes on 105 days (85% of the available time) during 1995. Both years were anomalous in terms of cloud-to-ground lightning, in that they were 20% and 53% below the typical territorial values of about 118,000 flashes per season (Table 2).

The number of lightning flashes peaked in the early summer months (June and July) with approximately 70–80% of the flashes occurring during these months, a typical seasonal variation (Lanoville, personal communication, 2000). Interestingly, Clodman and Chisholm (1996) found that 55% of flashes in the southern Great Lakes region peaked during these two months, and Reap and Orville (1990) reported that 60% of the flashes found over the north-eastern United States occurred during these months. Lightning, therefore, peaks during the same time period as in these other regions, but is more concentrated over the Mackenzie Basin within this period.

The spatial distributions of the total lightning strike activity during 1994 and 1995, and the corresponding fraction of positive strikes, are shown in Fig. 2. The lightning frequency maps were produced at a 1 degree latitude by 1 degree longitude resolution. The grid accumulations over the basin represent a wide range of lightning densities. For example, the strikes detected at latitude 65°N vary between 17–640, 22–1040 strikes at latitude 60°N, and 3–2238 strikes at latitude 57°N, and represent, equivalent lightning densities of 0.3–12.4 strikes per 100 km^2, 0.4–17.0 strikes per 100 km^2, and 0.1–33.5 strikes per 100 km^2, respectively. At the edge of the basin where the number of strikes is low, the fraction of positive lightning activity may be misleading because the sampling size is small (see Fig. 2, middle panel, as an example).

Some of the observations and interpretations arising from this information follow:

- During 1994, the area of maximum lightning activity (bounded by strike accumulations greater than 1000) extended from the wetlands region between Trout Lake and

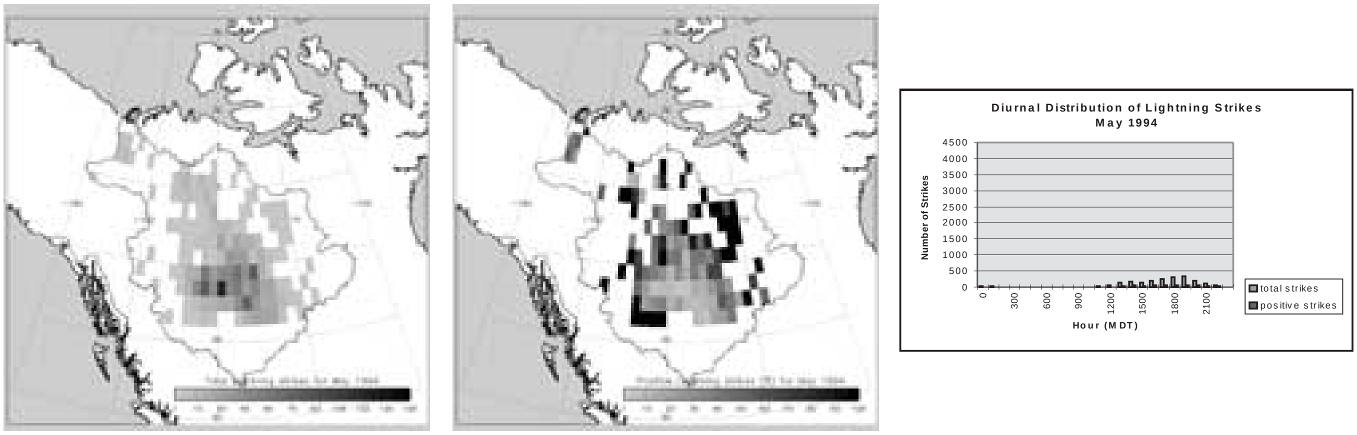

Total Strikes in 1994

Total Strikes in 1995

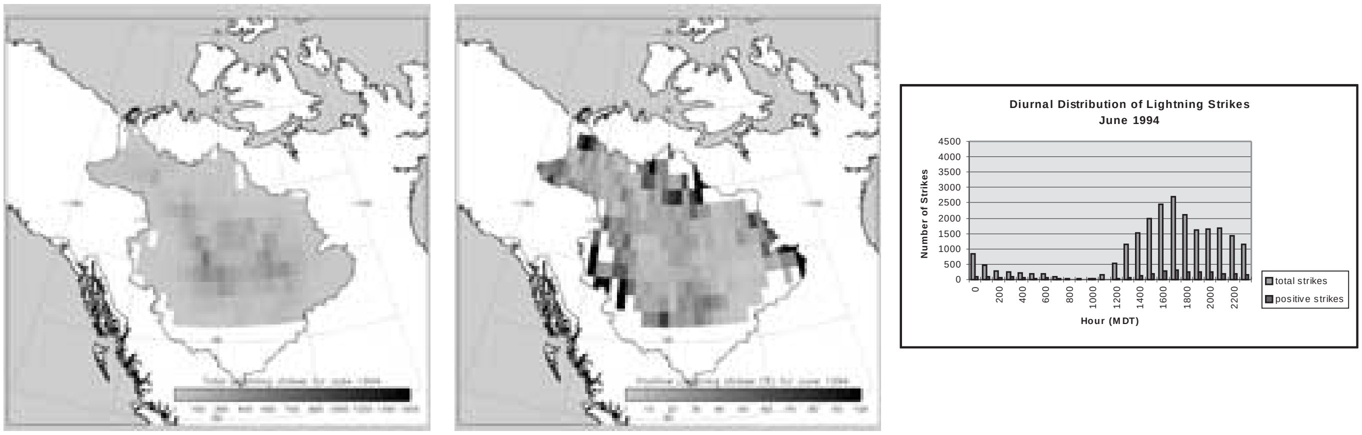
% Positive Strikes in 1994

% Positive Strikes in 1995

Fig. 2 A summary of the seasonal distributions of lightning during 1994 and 1995. The top panel summarizes the spatial distribution of the total lightning strike activity in one degree latitude by one degree longitude grid resolution. The middle panel summarizes the fraction of positive strikes (expressed as a percentage) for the corresponding grid elements. The bottom panel summarizes the diurnal variation of the total cloud-to-ground lightning strikes and the positive lightning strikes.



May 1994 (Total strikes) May 1994 (% Positive strikes)



June 1994 (Total strikes) June 1994 (% Positive strikes)

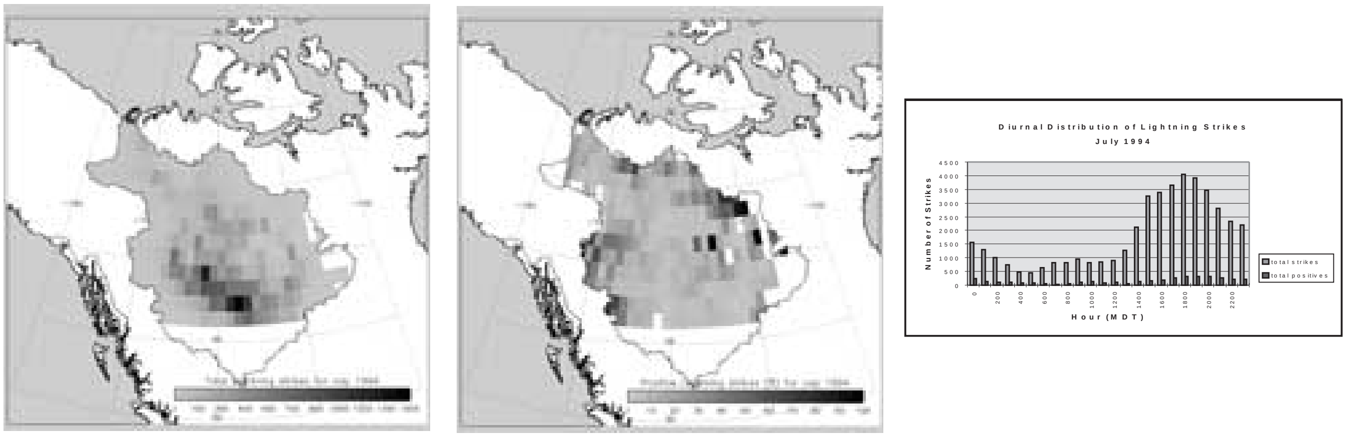
Fig. 3 A summary of the monthly distributions of lightning during 1994. The panels on the left illustrate the spatial distribution of the total lightning strike activity in one degree latitude by one degree longitude grid resolution for each month. The middle panels reflect the fraction of positive strikes (expressed as a percentage) for the corresponding grid elements. The panels on the right show the diurnal variation of the total cloud to ground lightning strikes and the positive lightning strikes.

the Kakisa River in the Northwest Territories through the Cameron Hills and Caribou Mountains and Naylor Hills region in northern Alberta (this area is highlighted in Fig. 1). The area of maximum activity shifted east in 1995. Two regions of major activity were observed (these areas are also highlighted in Fig. 1). One region was located near the Peace-Athabasca delta and the other region was located to the east of the Caribou Mountains in a sector with an abundance of small warm lakes (Bussières, this issue). These observations suggest that wetlands and small lake areas may be acting as local moisture sources to feed thunderstorms or to enhance thunderstorm activity.

- Fewer strikes occurred over the large lakes within the basin than over the surrounding land areas. This implies that the cold lake surfaces (Bussières, this issue) can significantly modify the intensity of the convective activity.
- The spatial distribution of the fraction of flashes lowering positive charge over the basin differed greatly between the two years. Most of the basin was characterized by a low fraction of positive strikes in 1994, while in 1995 a large portion of the basin showed high fractions of positive strikes. This suggests that the nature of thunderstorms or at least their electrification processes over the basin were different.

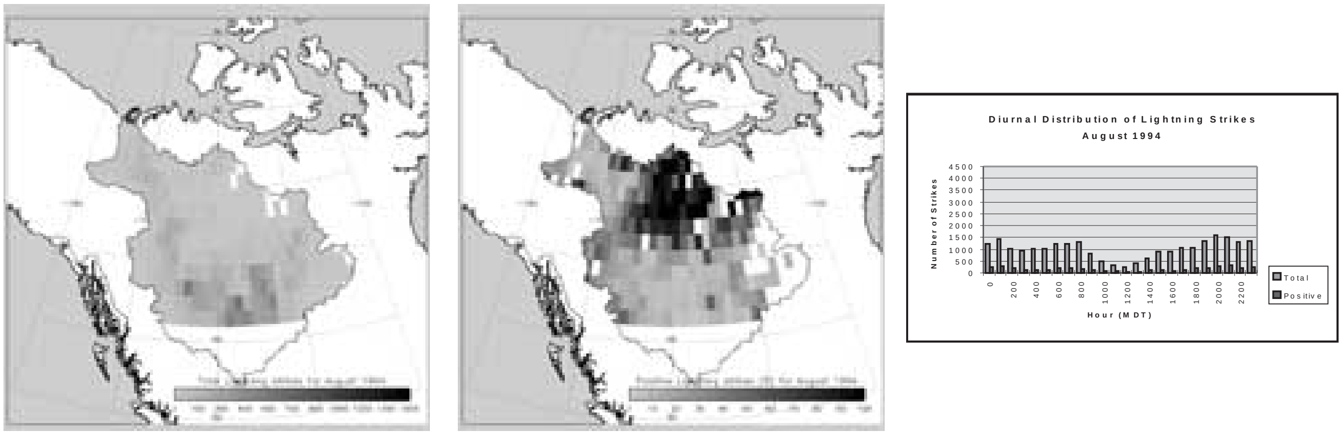
Information on the monthly spatial distributions of the total lightning strike activity, and the fraction of positive strikes during 1994 and 1995 is shown in Figs 3 and 4, respectively. These figures illustrate a number of points including:

- Lightning activity patterns exhibited broad variability. In the early part of the season, regions of greatest activity were located near Fort Simpson and near Fort Smith in the Northwest Territories. Maximum lightning activity moved south into northern Alberta by late July and August. The spatial variability of the lightning activity undoubtedly reflects the controlling influence of synoptic and mesoscale



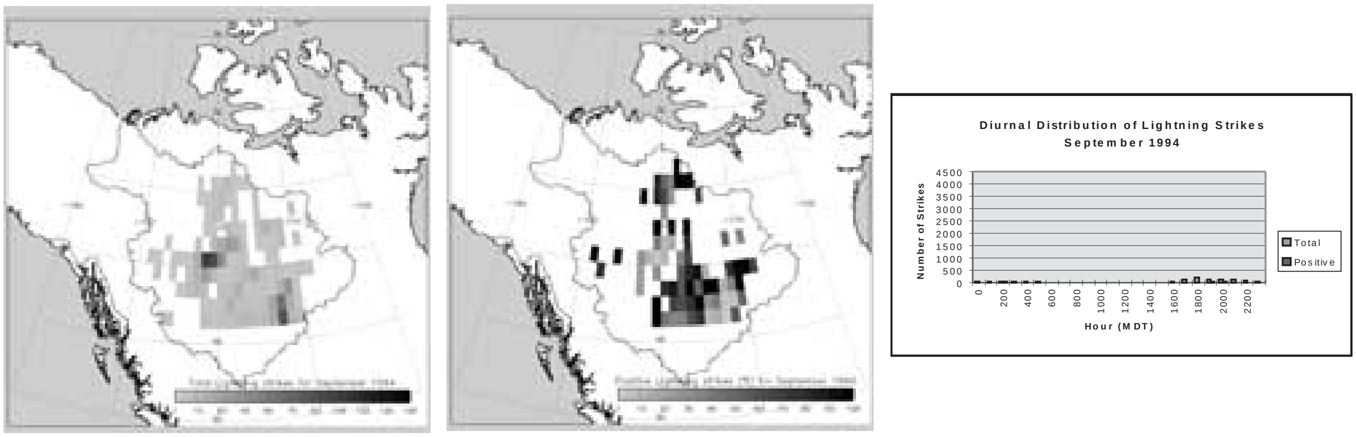
July 1994 (Total strikes)

July 1994 (% Positive strikes)



August 1994 (Total strikes)

August 1994 (% Positive strikes)



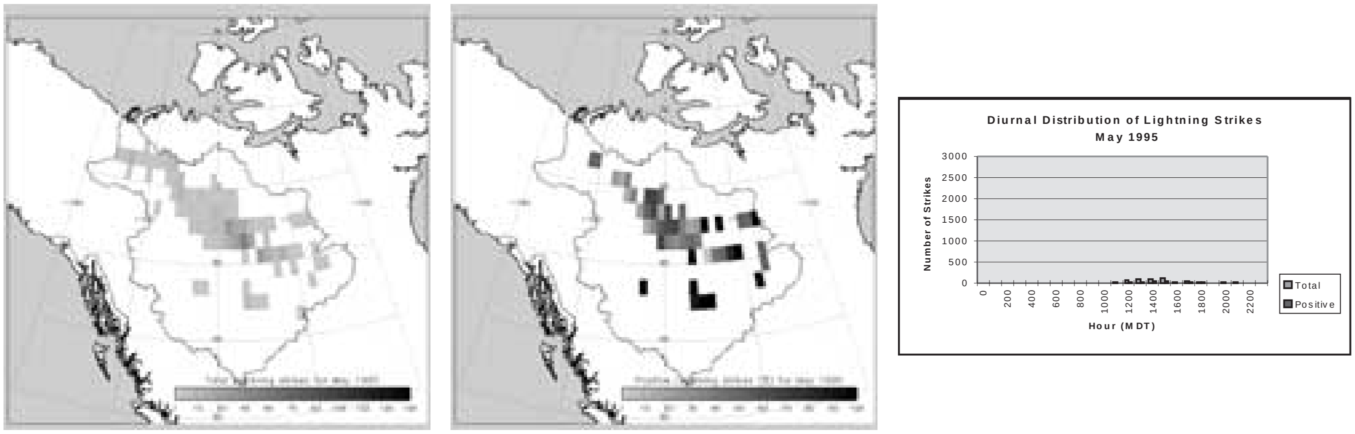
September 1994 (Total strikes)

September 1994 (% Positive strikes)

Fig. 3 (*Concluded*)

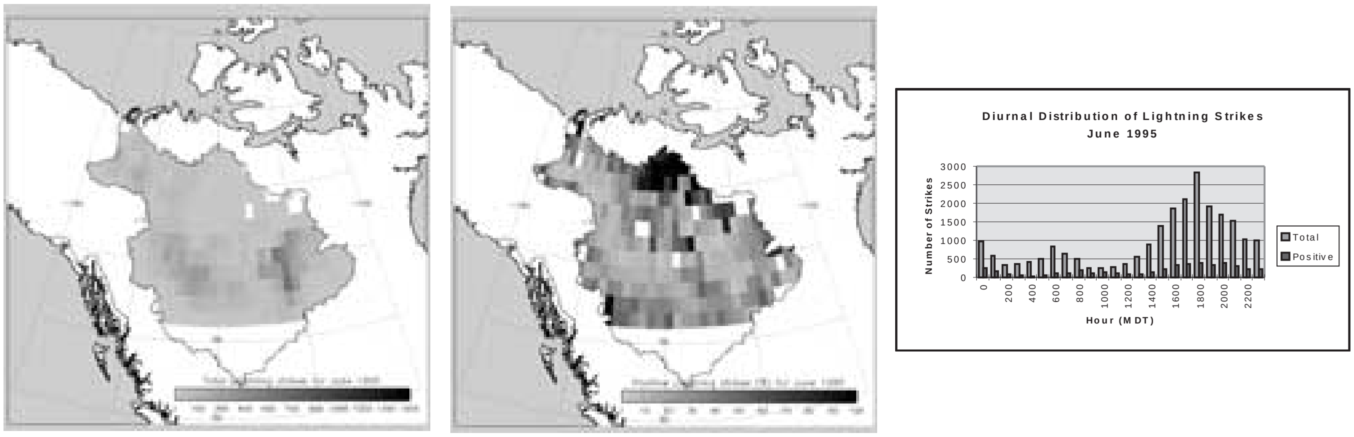
flows as well as the influence of the wetlands, small warm lake areas, and orography.

- Although lightning activity was low in May and September, high fractions of positive strikes were observed during these two months. The same observations were made in north-western Ontario (Flannigan and Wotton, 1991), and may be related to the nature of the convection during these colder months (Engholm et al., 1990). Also, an increase in positive lightning has been reported in low-level, winter-time thunderstorms (Takeuti et al., 1978); such weak con-



May 1995 (Total strikes)

May 1995 (% Positive strikes)



June 1995 (Total strikes)

June 1995 (% Positive strikes)

Fig. 4 As in Fig. 3, except for 1995.

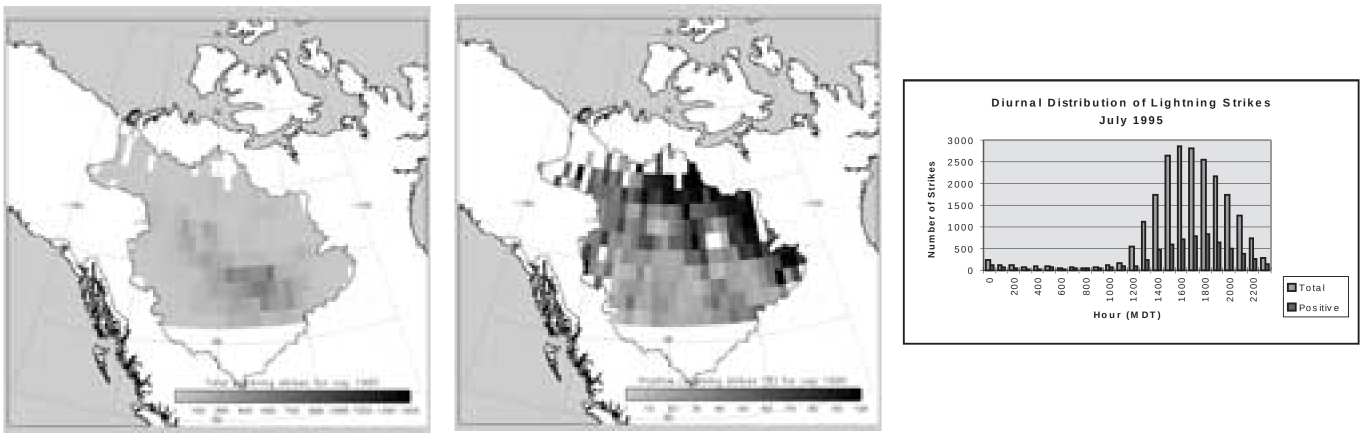
vective activity may be more characteristic of the May and September periods over the Mackenzie basin.

The diurnal variations of lightning during the summers of 1994 and 1995 (Fig. 2) show that the majority of the lightning strikes occurred in the mid-afternoon. However, some nocturnal activity occurred over the basin as well. In particular:

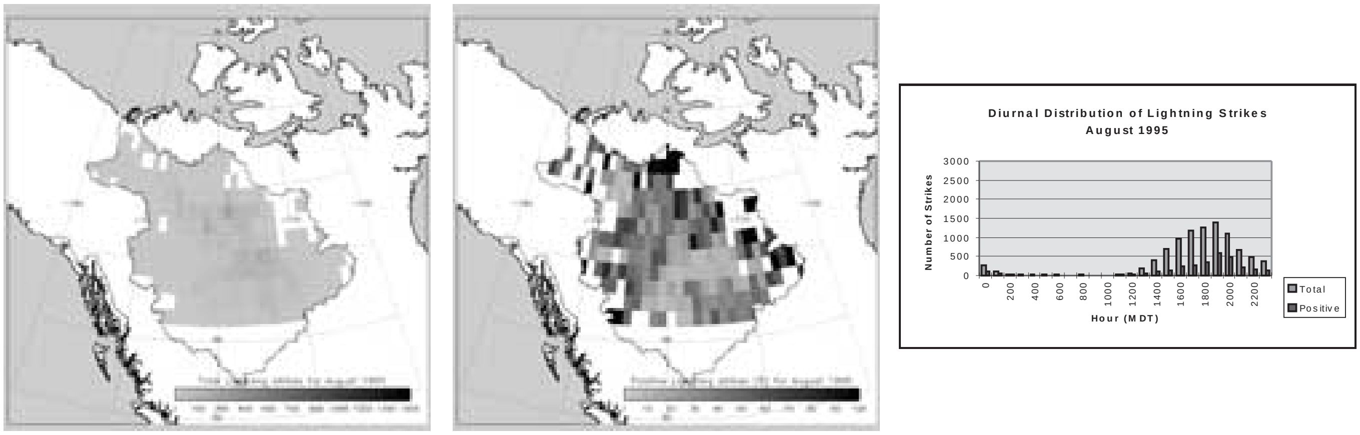
- The lightning data showed a peak in activity near 18:00 local time in both years. However, the distribution showed a more dramatic peak at this time in 1995 than in 1994. Nonetheless, this information suggests that airmass thunderstorms produce the bulk of lightning over the Mackenzie basin.
- There were more nocturnal strikes in 1994 than in 1995 with 28% of the strikes occurring between 22:00 and 06:00 local time in 1994 and 17% occurring between these times in 1995. This suggests that the thunderstorms in 1994 were longer lasting than those in 1995.
- The positive strike peak activity occurred about one hour later than the maximum strike occurrence time, near 19:00 local time. This suggests that positive strikes may be a characteristic of thunderstorms in their late mature or dissipating stages, at least over this region.

Collectively, these observations indicate that the years 1994 and 1995 marked a very unusual period for lightning activity over the Mackenzie basin. There was a relatively low amount of lightning activity but an unusually high fraction of positive lightning strikes during 1995, even though precipitation for this period was far below normal (Stewart et al., this issue). A critical question therefore is linked with the manner in which the lightning was produced with so little precipitation. Stewart et al. (this issue) found that cloud bases were higher than normal during these periods. Certainly this would contribute to more loss of precipitation by evaporation below cloud base.

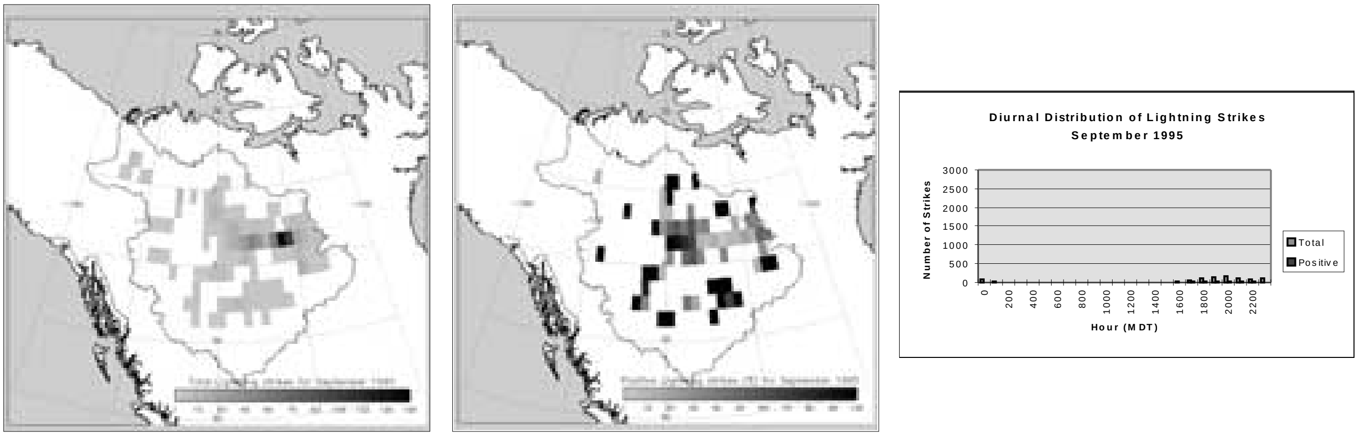
The high fraction of positive lightning activity is another puzzling issue. There is evidence that thunderstorms entraining smoke from forest fires may exhibit enhanced positive cloud-to-ground lightning activity (Lyons et al., 1998; Murray et al., 2000). The aerosols and ice nuclei produced by



July 1995 (Total strikes) July 1995 (% Positive strikes)



August 1995 (Total strikes) August 1995 (% Positive strikes)



September 1995 (Total strikes) September 1995 (% Positive strikes)

Fig. 4 (*Concluded*)

the smoke (Hobbs and Radke, 1969; Hobbs and Locatelli, 1969) may be changing the cloud microphysical processes, which in turn may be altering the electrical characteristics of the storms (Williams et al., 1991). To examine whether these ideas are plausible, the visibility element recorded at several weather stations in the basin was used to determine qualitatively if smoke was present. The number of days with visibility reduced to 9.6 km or less in smoke or haze, for the summer months between 1964–1998 at Fort Simpson is shown in Fig. 5. Two anomalous periods stand out; 1979–81 and

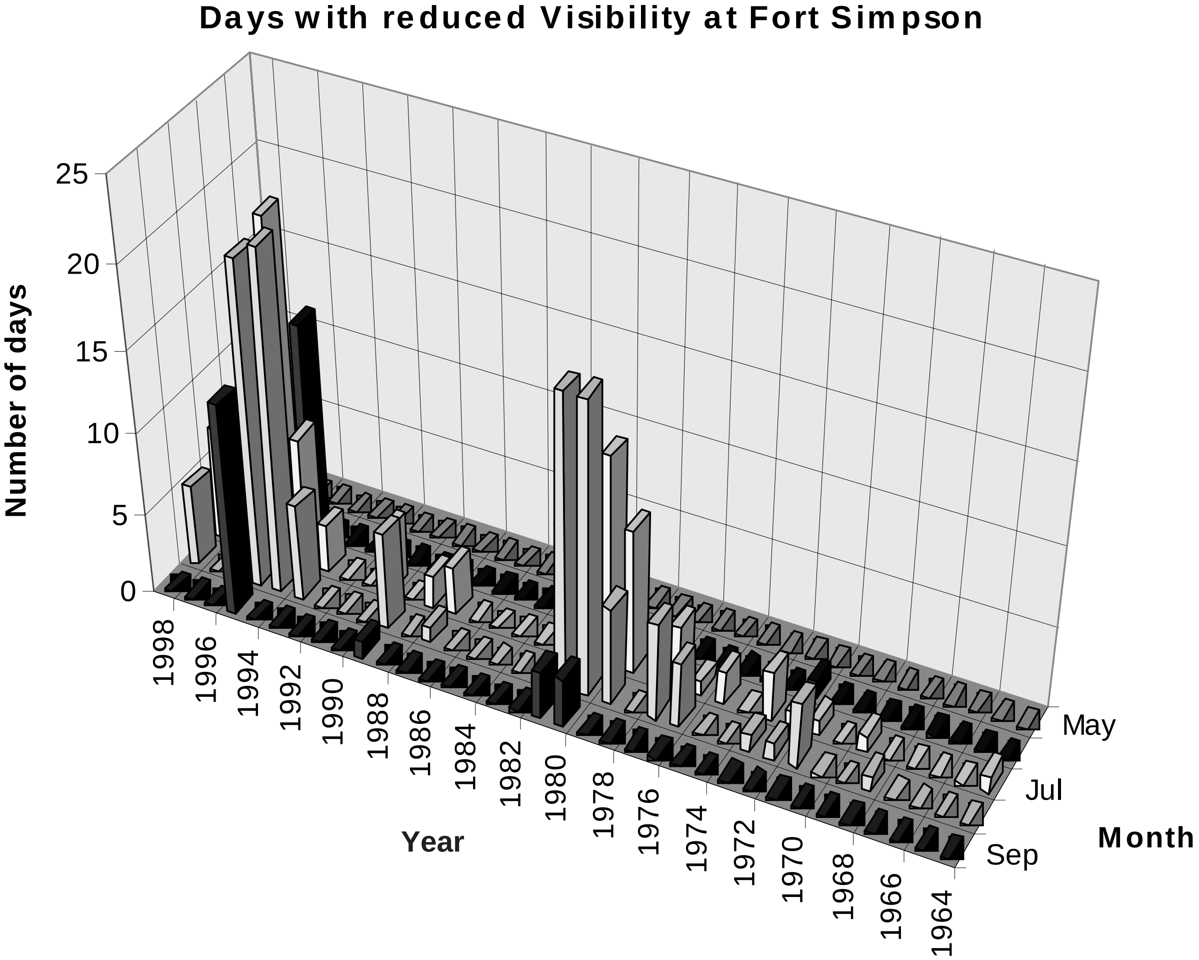


Fig. 5 The number of days, between May and September, with visibility reduced to 9.6 km or less in smoke or haze, for the period 1964–1998 at Fort Simpson.

1994–95. On average, there are seven days of reduced visibility events due to smoke or haze, at Fort Simpson, between May and September. During the summer of 1995, there were 67 days with reduced visibility. A National Oceanic and Atmospheric Administration High Resolution Picture Transmission (NOAA HRPT) satellite photo taken on 13 July 1995 at 01:00 UTC is shown in Fig. 6 as an illustrative example of the conditions associated with these low-visibility occurrences. This composite of the visible, near infra-red and infra-red bands clearly shows a layer of smoke extending over Great Bear Lake.

Although the evidence is circumstantial, the smoke may have contributed to the enhanced positive lightning activity in 1995. It should be noted that the summers of 1994 and 1995 also experienced some of the lightest surface winds on record (Stewart et al., this issue). These observations suggest that a series of feedbacks may have been occurring. Daytime heating would trigger thunderstorm development, which would travel slowly through the basin producing lightning and igniting forest fires in the dry areas. The forest fires would produce smoke, which would persist in the basin because the low-level winds were not strong enough to advect the smoke out of the basin. The smoke would interact with more thunderstorms altering the electrical characteristics of the storms, which in turn produced more positive lightning flashes and more forest fires.

5 Forest fire activity in 1994–95

Severe convective storms and associated lightning activity generate major forest fires in Canada in general and within the boreal ecosystem of the Mackenzie basin in particular. Lightning accounts for approximately 35% of forest fire ignitions in Canada (Weber and Stocks, 1998) and 85% of the total area burned. Area-burned statistics are influenced by a number of factors including the forest extent, the topography, the composition of the landscape, fire suppression policies and priorities, organizational size and efficiency, fire site accessibility, and weather. As an example, Flannigan and Harrington (1988) examined the relationship between meteorological variables and area burned. They found that severe fire months were very dependent on rainfall frequency, temperature and relative humidity, and independent of rainfall amount.

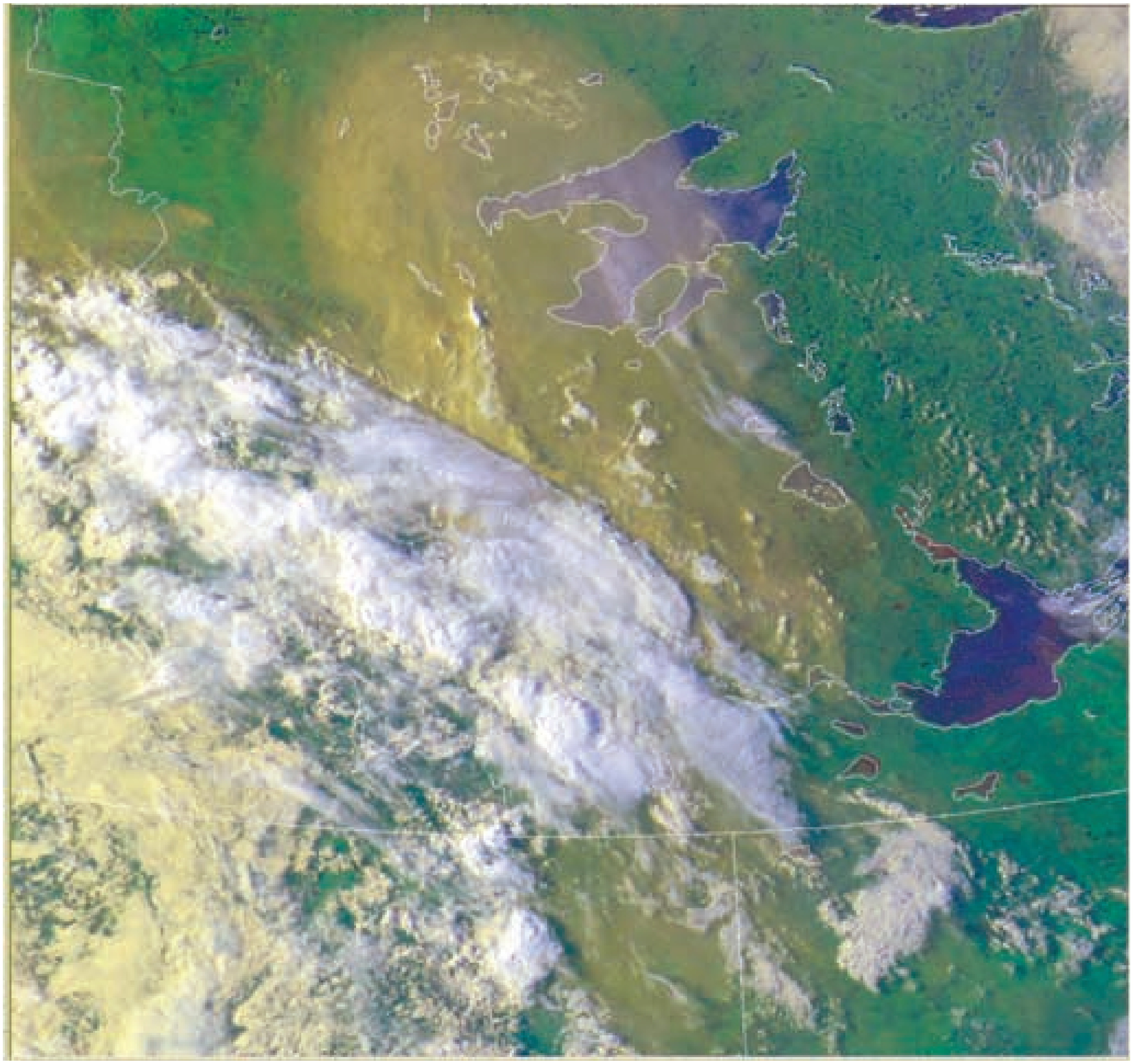


Fig. 6 A NOAA satellite image over the Mackenzie basin acquired on 13 July 1995 at 01:00 UTC.

The Mackenzie River basin encompasses five fire management jurisdictions. The Alberta portion of the basin (representing approximately 23.5% of the total basin area) is the responsibility of Alberta Environment's Forest Protection Branch. Approximately 80% of the provincial fire starts and burned areas occur within this region (Nimchuk, personal communication, 2000). The Government of the Northwest Territories (NWT) Forest Management Branch maintains responsibility for the NWT (representing approximately 47.1% of the total basin area), while the British Columbia Ministry of Forests, Yukon Fire Management Branch of Indian and Northern Affairs Canada, and the Saskatchewan Environment and Resource Management are responsible for the British Columbia, Yukon Territory and Saskatchewan regions of the basin, (representing approximately 15.5%, 7.3% and 6.6% of the basin area), respectively.

Annual forest fire statistics derived from the last ten years (1990–1999) indicate that lightning typically starts approximately 65% of the average 1578 forest fires in the Mackenzie basin. The total number of fires is underestimated, as the extreme north of the Yukon Territory is the most remote and inaccessible corner of the Territory that burns regularly and

TABLE 3. A summary of forest fire and lightning statistics in the Mackenzie River basin (by jurisdiction).

		Area in Basin (km^2)	1994	1995	1990–99 average	Fire Management Jurisdiction
Alberta		422,653				*Alberta Environmental Protection - Forest Protection Branch (except National Parks)*
	Total number of fires		698	643	774	
	Total area burned (ha)		23,654	268,918	103,179	
	Total area burned (ha) (Lightning caused)		21,645	260,163	94,662	
	Lightning-ignited fires (%)		57	45	61	
Northwest Territories		845,992				*Government of the Northwest Territories - Forest Management Branch (except National Parks)*
	Total number of fires		627	215	319	
	Total area burned (ha)		3,009,433	2,827,367	958,050	
	Total area burned (ha) (Lightning caused)		2,994,516	2,711,015	907,160	
	Lightning-ignited fires (%)		81	60	80	
British Columbia		279,369				*British Columbia Ministry of Forests*
	Total number of fires		590	302	415	
	Total area burned (ha)		4,733	14,736	13,816	
	Total area burned (ha) (Lightning caused)		3,659	9,898	6,449	
	Lightning-ignited fires (%)		79	37	62	
Yukon Territory		131,287				*Indian and Northern Affairs Canada, Yukon Fire Management*
	Total number of fires		30	15	24	
	Total area burned (ha)		31,852	14,899	22,276	
	Total area burned (ha) (Lightning caused)		31,850	14,870	22,236	
	Lightning-ignited fires (%)		83	53	57	
Saskatchewan		118,261				*Saskatchewan Environment and Resource Management*
	Total number of fires		72	25	46	
	Total area burned (ha)		369,338	145,730	118,520	
	Total area burned (ha) (Lightning caused)		158,855	58,292	79,408	
	Lightning-ignited fires (%)		38	55	48	

some fires have certainly escaped detection (Milne, personal communication, 2000). These forest fires typically burn approximately 1.11 Mha over the basin (Table 3). Over the NWT alone, lightning typically starts approximately 80% of the forest fires (Epp and Lanoville, 1996) and the fires typically consume approximately 908 Kha (Table 3). The burn areas in the NWT during 1994 and 1995, approximately 3 Mha each year, were very unusual (Table 3 and Fig. 7). Although 1994 produced less area burned than usual in Alberta, the 1995 season was associated with much higher values (260 Kha) than normal. In fact, 1994/95 was the worst 2-year period on record for area burned in Canada (Simard, 1997).

The actual ignition of forest fires by lightning depends on a number of factors. These include: the type, density and depth of the organic material such as grasses and dead leaves (referred to as fuel) that is struck by the lightning; fuel moisture; ventilation; and characteristics of the lightning discharge. In regards to this latter factor, it is important to note that some cloud-to-ground lightning flashes have a long continuing current (that is, the current has a slow decay rate after reaching a peak). There is some evidence that long continuing current flashes are more likely to start fires than other cloud-to-ground flashes because they would expose fuels to heat for longer periods of time (Fuquay et al., 1972). In addition, studies have shown that more than 50% of all positive discharges have a long continuing current component (Beasley et al., 1983), whereas only 25–50% of negative discharges have a long continuing current component (Uman and Krider, 1989).

To provide an objective measure of ‘fire weather’, a seasonal severity rating (SSR) is determined. The national SSR values are generated from a network of approximately 250 weather stations where the noon reading of temperature, relative humidity, wind speed and 24-h precipitation amounts are used to calculate the Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987). The SSR is the average of the daily severity rating (DSR) for 1 May – 31 August inclusive.

Given this background information, the SSR maps for 1994 and 1995 are shown in Fig. 8. Severity ratings greater than 2 reflect weather conditions suitable for extensive burning (Stocks et al., 1981). The maps indicate that the basin was in a relatively high fire danger classification each year. However, one has to be cautious in applying SSR too rigorously. Harvey et al. (1986) showed that although the SSR for 1981 was slightly higher than that for 1980, the area burned in northern Alberta in 1981 was approximately double that of the previous year. Fire activity depends on the actual weather, fuels, ignitions and human activities (for example, fire management).

The seasonal distribution of lightning and lightning-ignited fires which burned areas greater than 200 ha is shown in Fig. 9. The majority of lightning-ignited fires occurred during

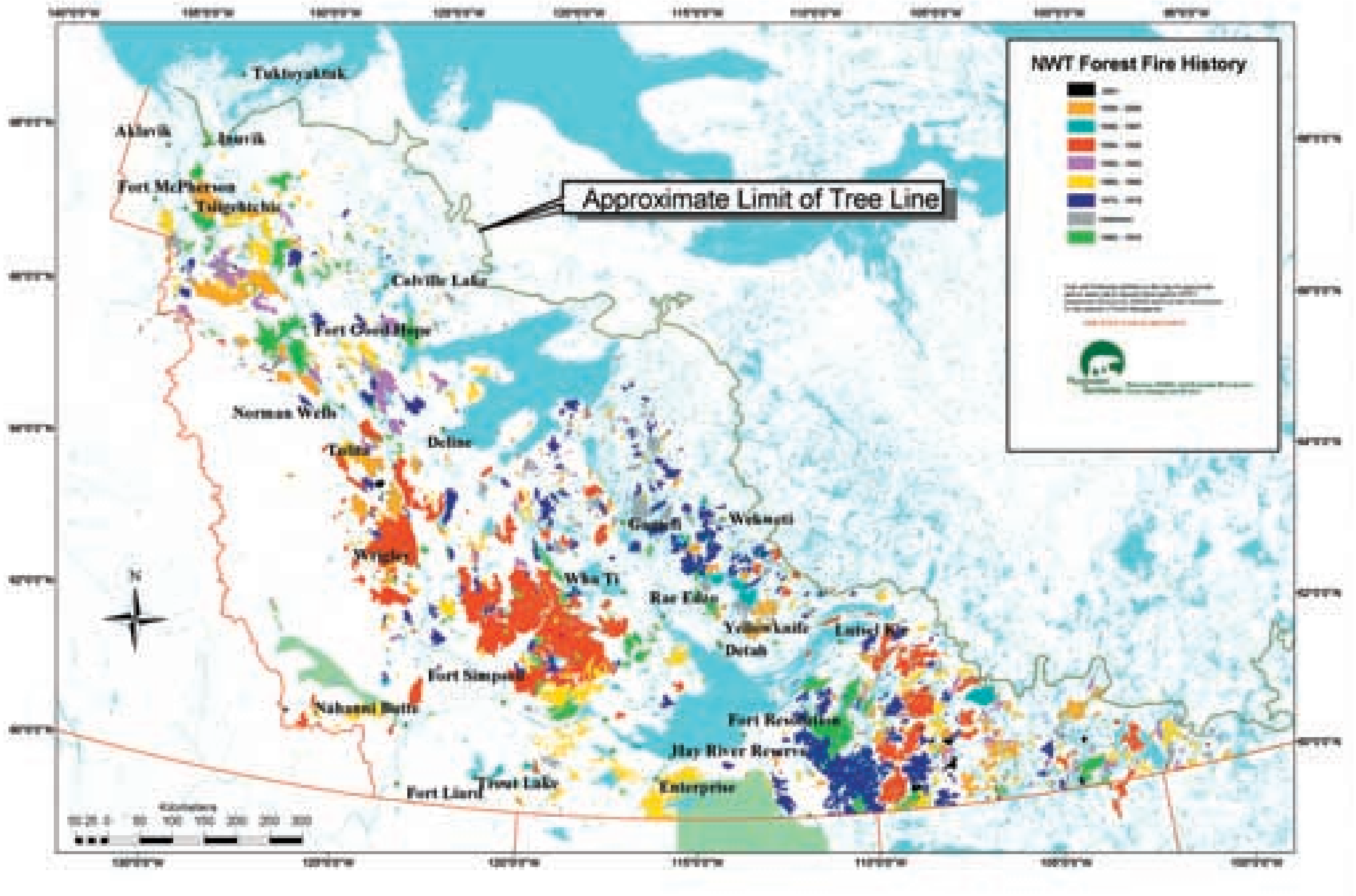


Fig. 7 A map depicting the forest fire history in the NWT from 1965 to 2001. Satellite image data analyses techniques and detailed surface characteristics were integrated with a geographic information system to prepare this map. The communities and fire region boundaries in the NWT are shown.

the most active lightning periods of both years. For example, 42 fires were ignited during July 1994, which was the most active lightning period that year, while 23 fires were ignited in June 1995, which was the most active lightning period that year.

The spatial distribution of these fires is shown in Fig. 10. In 1994, many of the fires that burned areas in excess of 100 Kha were located east of Great Slave Lake, where SSR index values were between 2 and 5. During 1995, the forest fires that burned such areas were found to be clustered in the region between Fort Simpson and Great Bear Lake where the corresponding SSR index values were between 5 and 10, and a second less concentrated cluster just west of the Peace-Athabasca district, where SSR index values were between 2 and 5 . One fire in the basin consumed an area in excess of 1 Mha.

Interestingly, these regions are also characterized by areas of higher fractions of positive lightning (Fig. 2). However, the fraction may be misleading when examining the role of positive lightning in the initiation of fires. The spatial distributions of the positive strikes during 1994 and 1995 are shown in Fig. 11. The number of positive strikes is higher in 1995 than in 1994 for those same regions.

Forest fires generally occurred in regions where surface conditions were favourable. Lightning over these regions acted as the trigger to initiate the fires. The 1995 positive lightning information is consistent with the initiation of the fires.

6 Atmospheric conditions

a *General Characteristics*

Some studies have been conducted on the large-scale atmospheric flows occurring during the forest fire season over the prairie and northern regions of Canada. For example, Street and Birch (1986) studied the surface and 50-kPa level features during the 1977–82 forest fire seasons within the Lake Athabasca - Great Slave Lake area. They found that, for 80% of the time, there was a dominant longwave ridge with a shortwave or longwave trough to the south or south-west of the ridge's position. Surface fields were characterized by a low pressure system located west of the study area with a trough through central Alberta and with high pressure areas both to the east and to the west of the surface trough position.

Other studies of synoptic conditions have also been carried out. Nimchuk (1983) and Harvey et al. (1986) pointed out the importance of the breakdown of the upper ridge and related

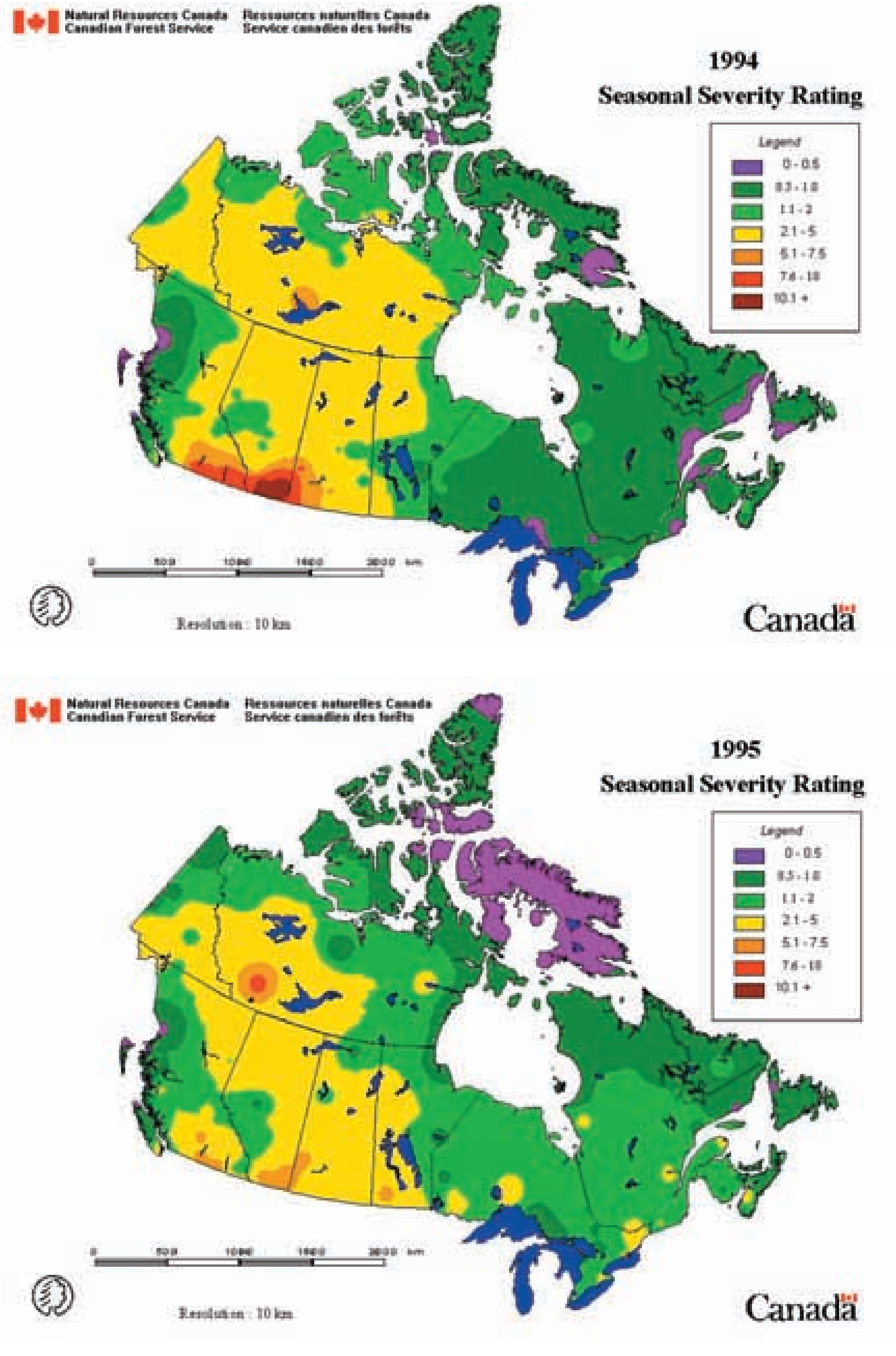


Fig. 8 The Canadian Seasonal Severity Rating maps for 1994 (top panel) and 1995 (bottom panel).

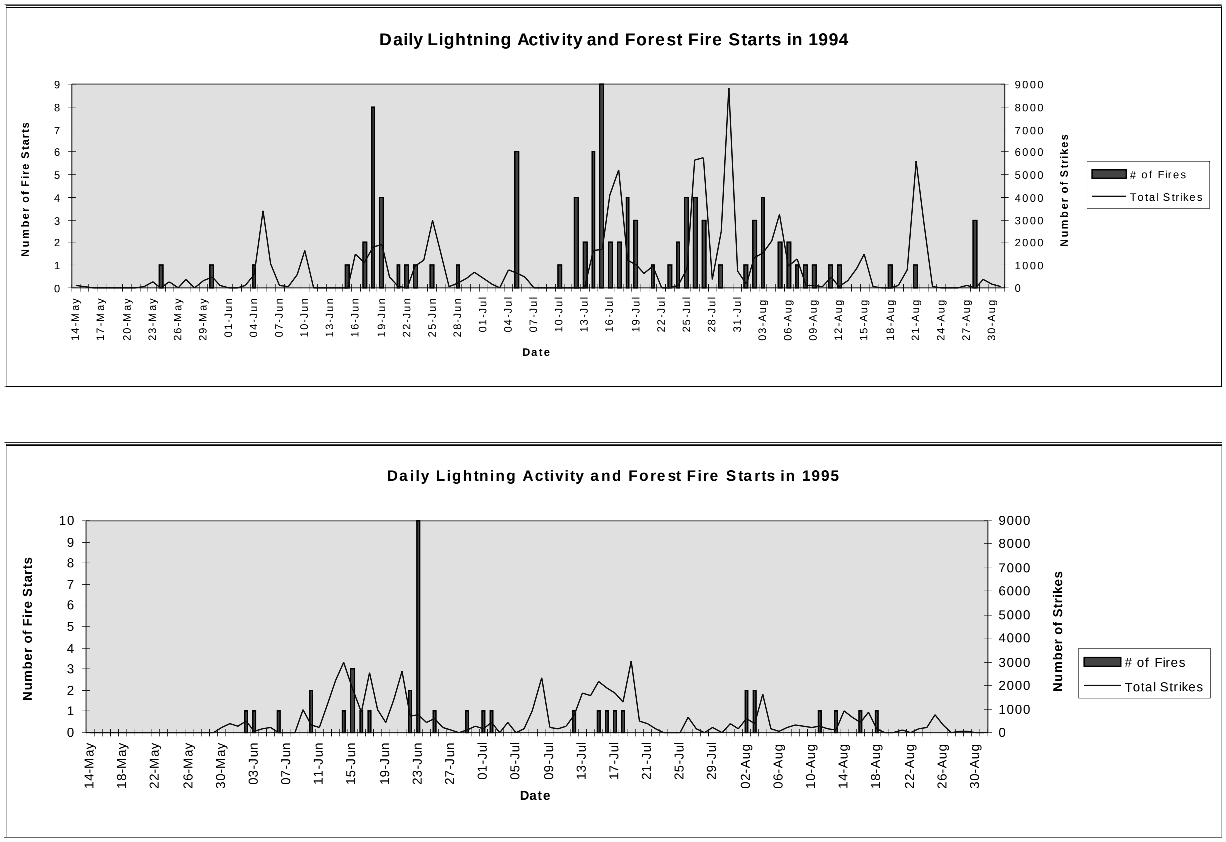


Fig. 9 The daily distribution of total lightning strikes (solid line) and the number of lightning-ignited forest fires (bars) in 1994 (top panel) and in 1995 (bottom panel).

forest fire occurrence. Nash and Johnson (1996) observed that the highest number of lightning strikes and largest number of forest fires in Alberta and Saskatchewan occurred when high pressure systems dominated. Brotak and Reifsnyder (1977) examined synoptic features associated with 52 major wildland fires (>2 Kha). They found that the vast majority of fires were associated with the eastern portion of small but intense shortwave troughs at 50 kPa. Skinner et al. (1999) found that 50-kPa height anomalies were well correlated with area burned by wildland fire over various regions of Canada.

Convection and lightning are, of course, linked with specific events associated with atmospheric instability. Instability varied substantially over the summer months of 1994 and 1995 over the Mackenzie basin. For example, Fig. 12 shows the Lifted Index for all sounding releases over these two years as well as long-term average values, derived from the Fort Smith upper air station. The Lifted Index was calculated by lifting a parcel from the surface dry adiabatically until saturated and then along a saturated adiabat to 50 kPa, a common operational technique. The temperature of the lifted parcel is then subtracted from the ambient temperature at 50 kPa to obtain the value of the Lifted Index.

The Lifted Index values indicate some important features. First of all, the general trends illustrate that the most unstable conditions generally occur during the June–July period, in agreement with the peak in lightning activity occurring during those months. Second, there is a very dramatic diurnal cycle to this index; instability (index value <0) rarely occurred at 12:00 UTC. Third, this figure also suggests that the two summer periods were characterized by a shift towards more instability than is typical. This shift, as earlier discussed, did not translate into more lightning strikes than normal over the whole year. Such measures of instability are therefore not a simple predictor of lightning occurrence, but they are necessary for lightning development.

In an attempt to determine the relationship between lightning severity, atmospheric instability and surface conditions, days in 1994 and 1995 when the network detected 500 or more lightning strikes were identified for further investigation. In addition, extreme events were defined as days with more than 2000 lightning strikes. The surface and upper air characteristics derived from the Fort Smith weather station and stratified by lightning strikes for these categories are summarized in Table 4. The information shown here indicates that extreme events occurred on slightly warmer days than is the case for the occurrence of more moderate lightning activity. The difference of 1.9°C is statistically significant, at the 90% confidence level, based upon a student’s t-test.

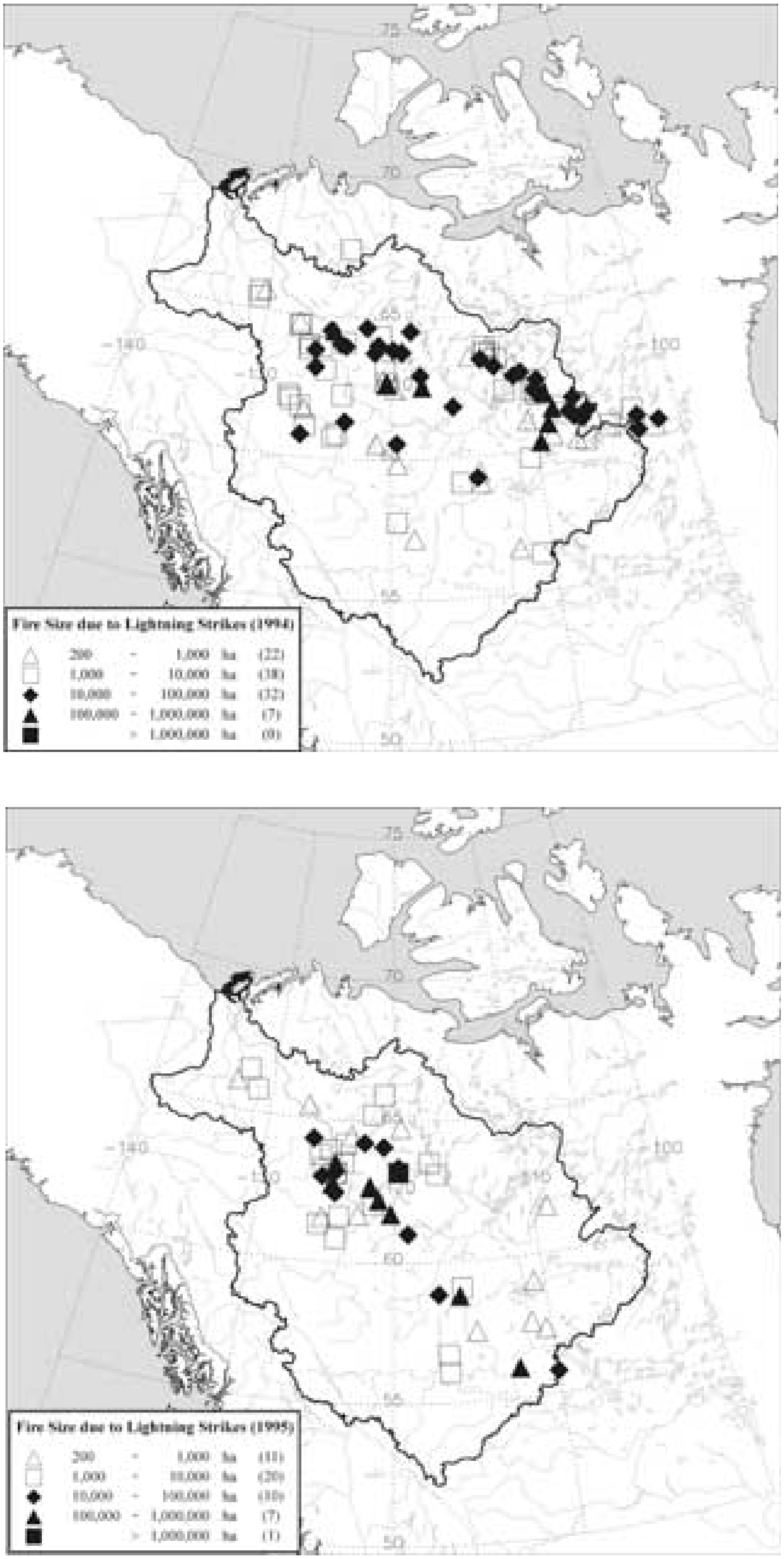


Fig. 10 The spatial distribution of lightning-ignited forest fire starts in 1994 (top panel) and in 1995 (bottom panel). The areas burned are denoted by different symbols.

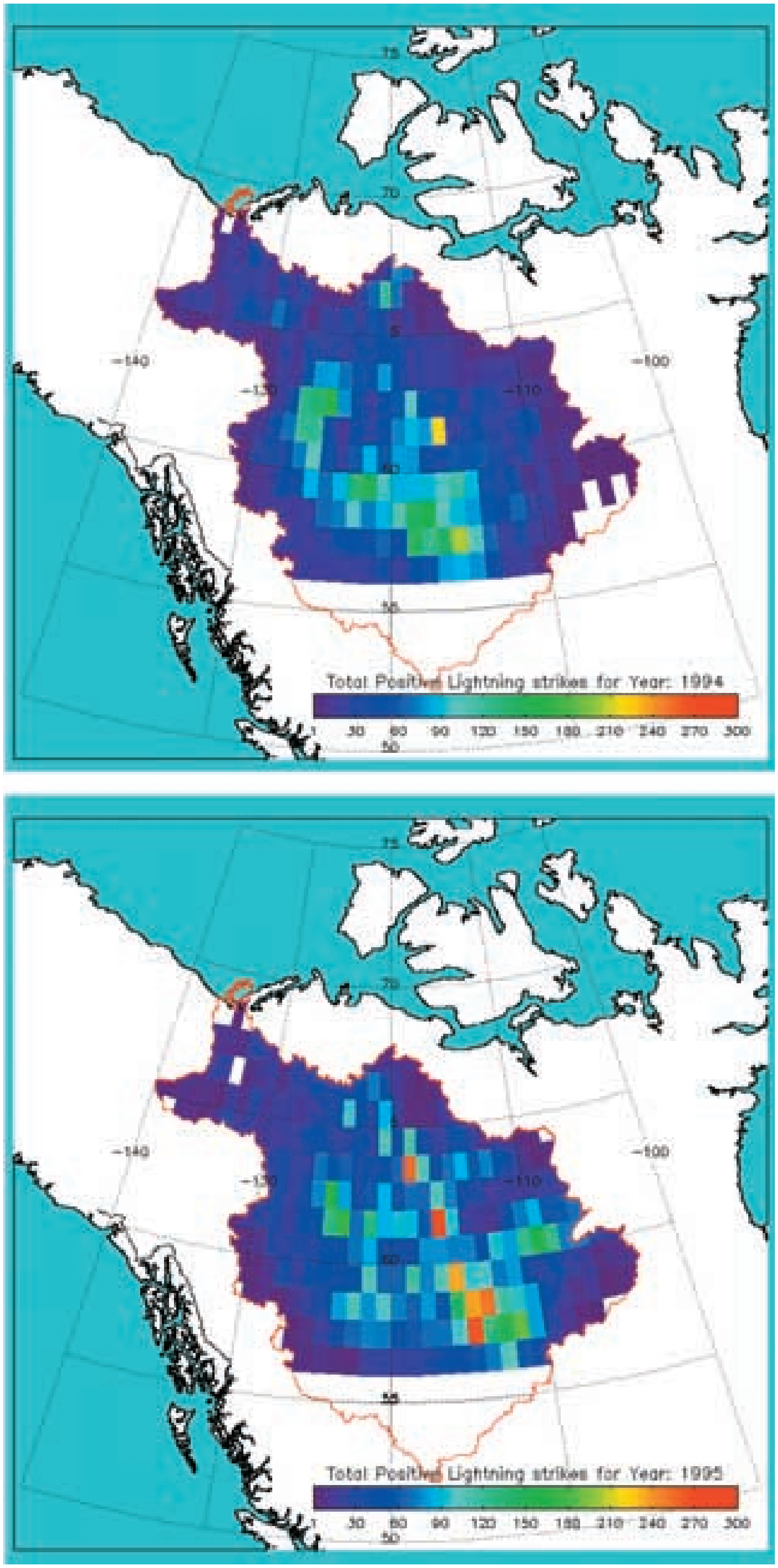


Fig. 11 A summary of the seasonal distributions of positive lightning during 1994 and 1995.

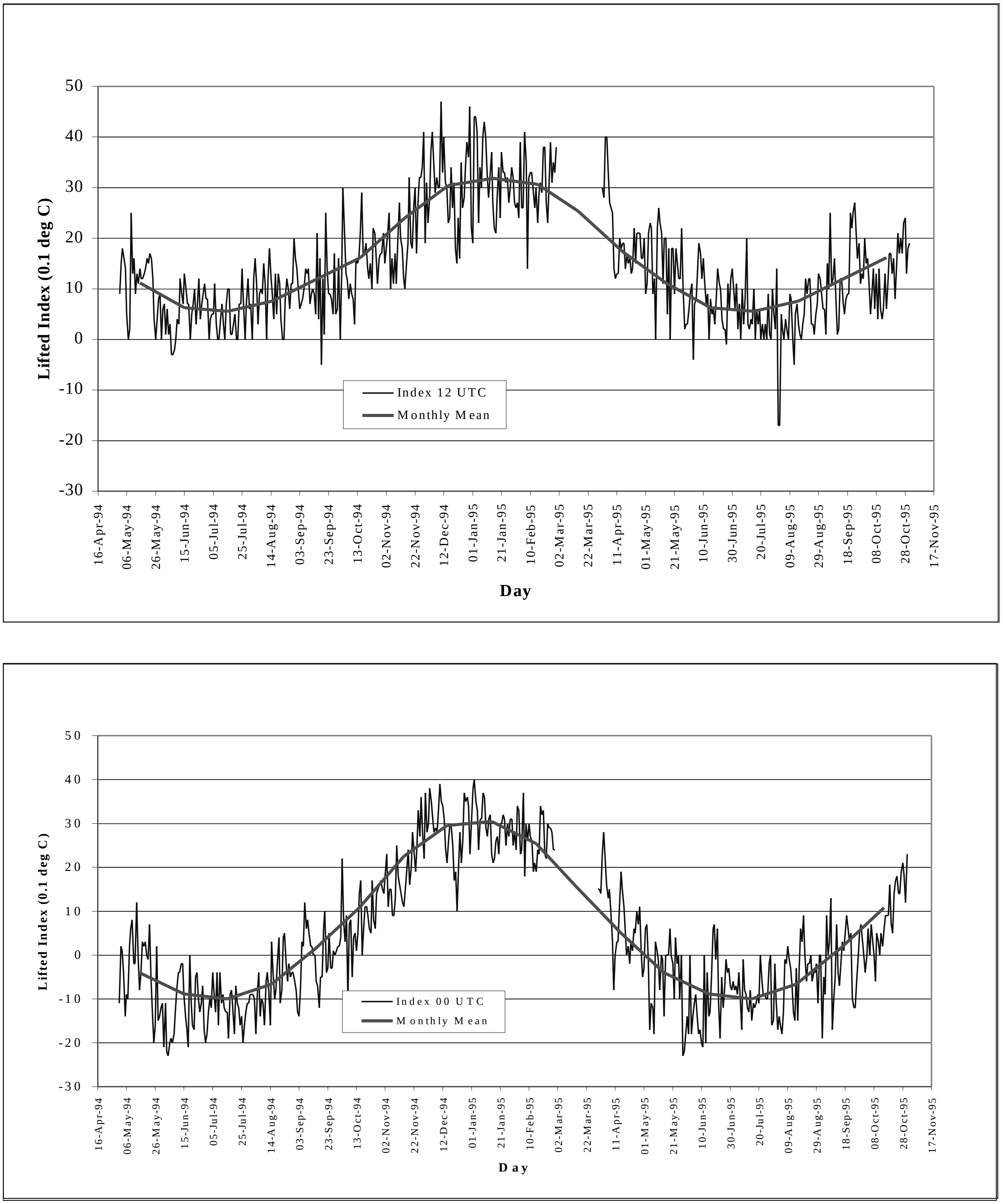


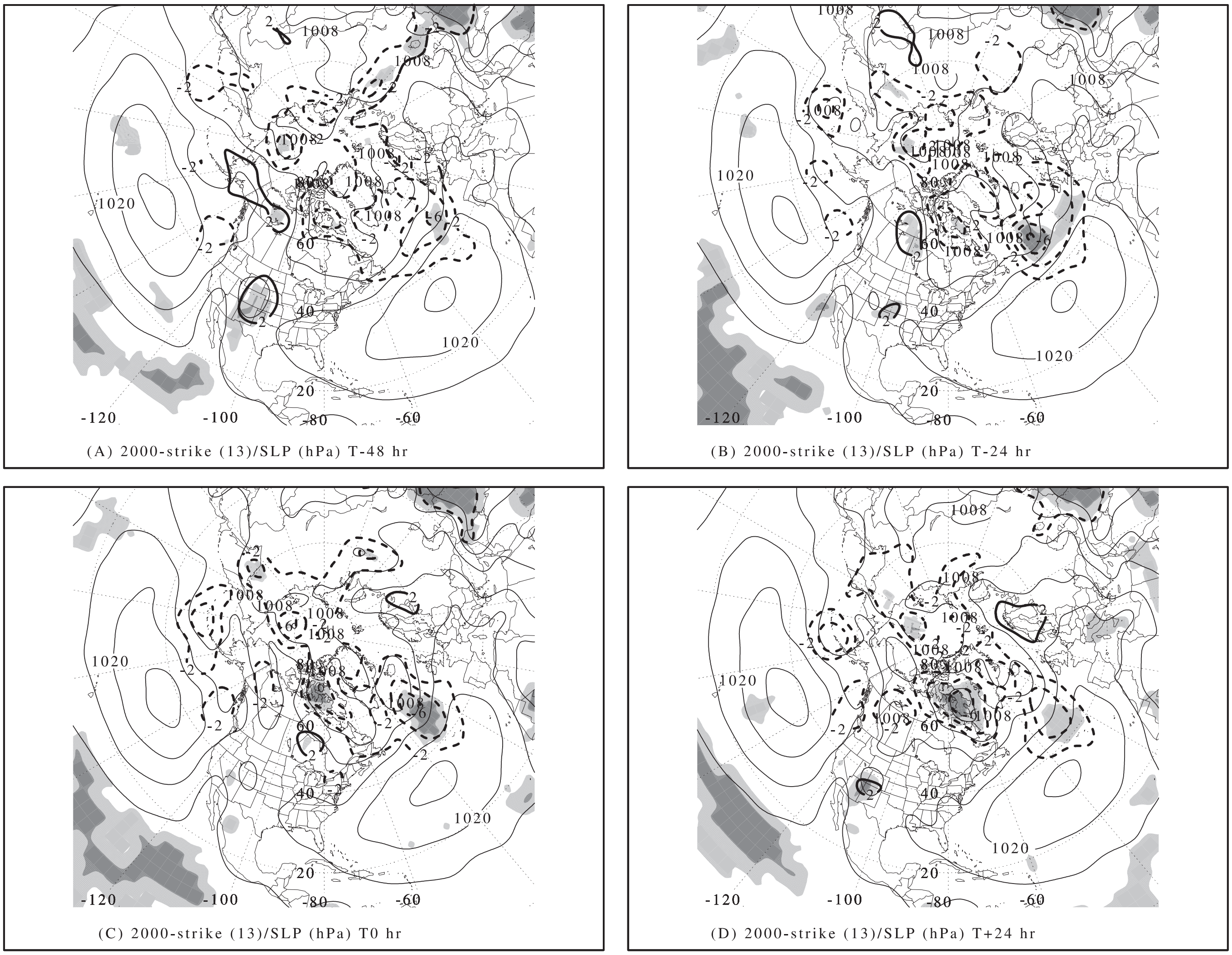
Fig. 12 The daily Lifted Index for the Fort Smith soundings at 00:00 and 12:00 UTC for the 1994/95 water year, and the monthly mean value based on the 40-year sample.

b *Composite Atmospheric Circulation Patterns*

To understand better the large-scale atmospheric circulation during the Mackenzie basin lightning events, the relevant sea-level pressure, 50-kPa, and 100–50-kPa thickness structures were studied. To accomplish this, the global gridded fields from NCEP (Kalnay et al., 1996) were used with a 2.5 degree latitude-longitude resolution. Anomalies of these fields, with respect to the 1963–96 reanalysis climatology, are shown to

TABLE 4. Summary of surface and upper air characteristics at Fort Smith, NWT associated with selected lightning days in 1994 and 1995.

Period 1994 – 1995	Units	Days >500 – 2000 strikes	Days > 2000 strikes
Number of days	–	55	19
Mean Lifted Index	deg C	–1.1	–1.2
Mean 50-kPa height	m	5649	5676
Mean daily maximum Temperature	deg C	23.2	25.1
Mean daily minimum Relative Humidity	%	38.6	42
Mean 100–50-kPa thickness	m	5570	5621


(A) 2000-strike (13)/SLP (hPa) T-48 hr

(B) 2000-strike (13)/SLP (hPa) T-24 hr

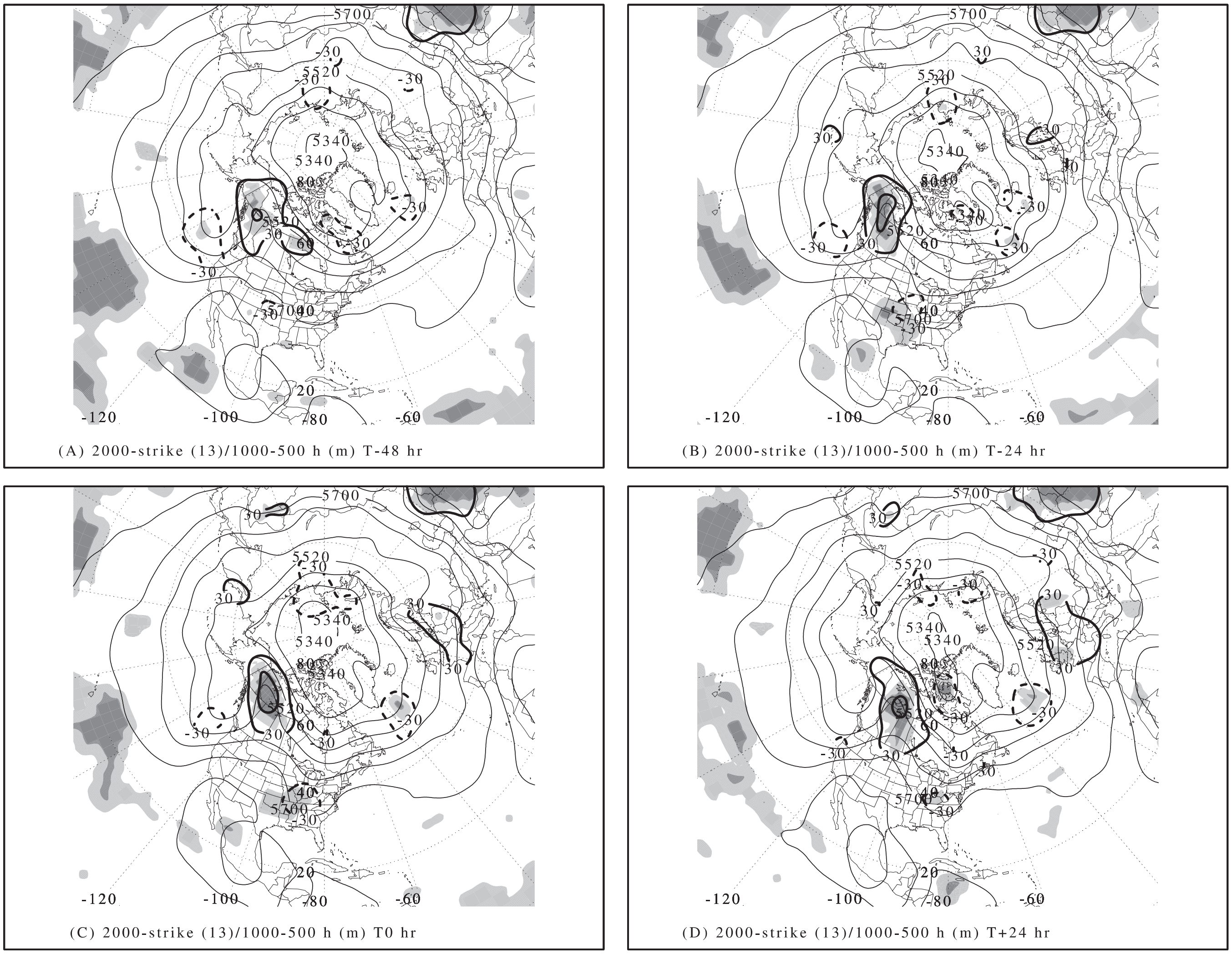
(C) 2000-strike (13)/SLP (hPa) T0 hr

(D) 2000-strike (13)/SLP (hPa) T+24 hr

Fig. 13 Composite sea level pressure (thin solid, interval of 0.4 kPa) and anomaly with respect to a 34-year climatology (thick solid for positive, interval of 0.2 kPa; thick dashed for negative, interval of 0.2 kPa) of 13 events in which at least 2000 lightning strikes occurred. Panels correspond to a) 48 h prior to, b) 24 h prior to, c) 0 h, and d) 24 h after the onset of the lightning strike event. Shaded areas show significance levels computed from the student's t-test of the anomalies with progressively darker shadings showing thresholds of 95% and 99% confidence limits.

provide a perspective on cases having at least 2000 strikes. Additionally, cases had to be separated by at least four days, so that each is assumed to be an independent synoptic-scale event. The mean, or composite, of the resultant 13 events, is then computed for the time T0, or 12:00 UTC of the event. Composites are also computed for 48 and 24 h prior to the event, and 24 h afterwards.

Sea-level pressure fields for these four times are shown in Fig. 13. Anomalies with respect to the 34-year climatology are also shown with shaded regions illustrating both 95 and 99% confidence limits according to the student's t-test. A similar procedure has been used by Lackmann and Gyakum (1996) for a cold-season precipitation composite in the Mackenzie basin. The large-scale features are similar to those


(A) 2000-strike (13)/1000-500 h (m) T-48 hr

(B) 2000-strike (13)/1000-500 h (m) T-24 hr

(C) 2000-strike (13)/1000-500 h (m) T0 hr

(D) 2000-strike (13)/1000-500 h (m) T+24 hr

Fig. 14 As in Fig. 13, except for the 100–50-kPa thickness, (thin solid, interval of 60 m, with the anomalies shown each 30 m.).

for a larger composite (not shown) in which a smaller number of daily strikes is included. The most obvious feature (Fig. 13) is a statistically significant ridge over Great Slave Lake two days prior to the event that travels south-eastward and weakens by T0 on the south-western side of Hudson Bay. The Mackenzie basin experiences enhanced southerly geostrophic flow during this 48-h period with gradually falling pressures. Persistent negative pressure anomalies in the Gulf of Alaska are associated with this enhanced southerly flow into the Mackenzie basin.

Figure 14, showing the 100–50-kPa thickness fields, reveals the presence of a statistically significant warm anomaly over the Mackenzie basin throughout the period. At the onset of the lightning events, the anomaly averages +90 dam, or nearly 5°C above the climatological mean. This anomalous warmth is consistent with the notion that thunderstorms in the Mackenzie basin are associated with strong solar insolation the effects of which extend through much of the troposphere. The slow eastward progression of this anomalously strong thermal ridge just downwind of the Mackenzie basin between T0 and T + 24 h is consistent with the concept that the thunderstorms are triggered by the passage of the upper-level ridge. This is also consistent with quasi-geostrophic concepts (Bluestein, 1993). The basic features are also similar to those discussed by Harvey et al. (1986), in which the surface ridge decays prior to the onset of the lightning events.

7 Concluding remarks

This, to our knowledge, is the first scientific paper concerned with the nature of lightning and deep convective activity over the Mackenzie basin and their relation to forest fire activity. The study focused on the summers of 1994 and 1995, which were characterized by record high forest fire burn areas, although it also examined general features. The study has led to several observations and conclusions.

The Mackenzie basin experiences relatively high lightning activity for such a northern location. This is linked to its geographic alignment, large-scale flows, and diurnal heating cycle. The convective storm season and resultant lightning activity in the Mackenzie Basin is characterized as short but intense with a strong peak in cloud-to-ground lightning during June and July. The maximum area of lightning activity is generally located south and south-west of Great Slave Lake, but varies in space and in time and is influenced by local moisture sources (such as wetland areas and small lakes) and by topography. The diurnal distribution of strikes indicates that most of the lightning is linked with daytime-heating initiated thunderstorms.

Conditions in the atmosphere and at the surface were very conducive, in 1994 and 1995, to record burn areas from forest fires. These two years were characterized by large-scale circulation patterns that have previously been found to be ideally suited to the development of forest fires. Strong instability was generated within the basin, primarily due to factors associated with the diurnal cycle, and the ensuing slow-moving, deep convective systems produced significant lightning activity including a substantial number of positive strikes. There is some evidence for a complex coupling between the circulation patterns, the storms, the forest fires, and the associated smoke that enhances forest fire activity, but this requires further investigation. The surface conditions were extremely dry over the region and the lightning was readily able to ignite the fires that persisted during the relatively precipitation-free summers.

In summary, the Mackenzie basin is greatly affected by the intertwined nature of convection, lightning, surface conditions and forest fires, and they combined in 1994/95 to produce extraordinary impacts.

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