Study of Cloud-to-Ground Lightning in Quebec: 1996–2005

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ABSTRACT *Using data from Hydro-Québec, a spatio-temporal summary study of cloud-to-ground lightning in Quebec (45°–53°N; 81°–65°W) for the 1996–2005 period was performed on a sample of close to four million lightning strokes. The annual number of lightning strokes and the ratio of negative to positive lightning (76:24) do not differ significantly from one year to the next. Despite the fact that there was an average of 239 lightning days per year, the lightning strokes were concentrated over a period of a few days. Between 1996 and 2005, 50% of the total annual lightning was distributed over 11 days, 75% over 25 days, and 90% over 44 days. Overall, the peak in the average annual cycle occurs on 15 July. Between 1996 and 2002, the number of days with at least one positive lightning stroke remained higher than the number of days with at least one negative lightning stroke. This tendency reversed from 2003 until 2005. Most of the annual lightning occurred during June, July and August. The average minimum number of lightning strokes per hour occurred at approximately 14:00 UTC, and the maximum number occurred at 21:00 UTC. The ratio of positive lightning to negative remained constant throughout the day.*

Both the density and the number of lightning days were mapped for the 10-year period. The spatial distribution of lightning indicates a higher density in the southern and western parts of the study area with an average of 0.52 to 1.27 lightning strokes km^{-2} yr^{-1}. The St. Lawrence Lowlands ecoregion receives the greatest number of lightning strokes annually (from 0.73 to 1.27 km^{-2} yr^{-1}). The spatial distribution of the number of lightning days per year is approximately the same as that of the density. The same two gradient axes can be observed crossing from north to south and from east to west. The spatial distribution of the percentage of positive lightning strokes varies considerably in the area, ranging from 0 to 65% depending on the location. While the St. Lawrence Lowlands ecoregion has the highest density and highest number of lightning days, it also has the lowest number of positive strokes. Additional research must be done to establish a correlation between our results and environmental variables, such as topography and vegetation, as well as the spatial variations of lightning and instances of forest fire.

RÉSUMÉ *[Traduit par la rédaction] À partir des données d'Hydro-Québec, nous avons effectué une étude spatio-temporelle sommaire des éclairs nuage-sol au Québec (45°–53°N; 81°–65°O) durant la période 1996-2005 sur un échantillon de près de 4 millions de décharges électriques. Le nombre annuel de décharges électriques et le rapport éclairs négatifs sur éclairs positifs (76/24) varie peu d'une année à l'autre. Même s'il y a eu en moyenne 239 jours d'éclairs par année, les décharges étaient concentrées sur une période de quelques jours. Entre 1996 et 2005, 50 % du nombre annuel total d'éclairs étaient distribués sur 11 jours, 75 % sur 25 jours et 90 % sur 44 jours. Dans l'ensemble, la crête du cycle annuel moyen se produit le 15 juillet. Entre 1996 et 2002, le nombre de jours avec au moins une décharge positive est demeuré plus élevé que le nombre de jours avec au moins une décharge négative. La tendance s'est inversée de 2003 à 2005. La plupart des éclairs pendant une année quelconque se sont produits en juin, juillet et août. Le nombre minimum moyen de décharges par heure s'est produit vers 14 UTC et le nombre maximum moyen s'est produit vers 21 UTC. Le pourcentage de décharges positives est demeuré constant durant toute la journée.*

Nous avons cartographié à la fois la densité et le nombre de jours d'éclairs pour la période de 10 ans. La distribution spatiale des éclairs révèle une densité plus élevée dans les parties sud et ouest de la région étudiée, avec une moyenne de 0,52 à 1,27 décharge km^{-2} an^{-1}. La région écologique des basses-terres du Saint-Laurent reçoit le plus grand nombre de décharges électriques sur une année (de 0,73 à 1,27 km^{-2} an^{-1}). La distribution spatiale du nombre annuel de jours d'éclairs est approximativement la même que celle de la densité. On peut observer les deux mêmes axes de gradient s'étendre du nord au sud et de l'est à l'ouest. La distribution spatiale du pourcentage de décharges électriques positives varie considérablement dans la région, allant de 0 à 65 % selon l'endroit. Bien que la région écologique des basses-terres du Saint-Laurent ait la plus forte densité et le

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plus grand nombre de jours d'éclairs, c'est dans cette région qu'on observe le plus petit nombre de décharges positives. D'autres recherches restent à faire pour établir une corrélation entre nos résultats et les variables environnementales, comme la topographie et la végétation, ainsi que les variations spatiales des éclairs et des feux de forêt.

1 Introduction

Lightning kills, on average, six people, seriously injures about 70 people and starts about 4000 forest fires in Canada annually. Approximately 2.7 million electrical discharges are recorded annually, and over the summer months there is a lightning strike every three seconds in Canada (Environment Canada, 2003). Although lightning causes only 35% of the forest fires in Canada, these fires are responsible for 85% of the total area burned (Stocks, 1991). The situation is similar in Quebec. According to the Société de protection des forêts contre le feu (SOPFEU), which provides aerial reconaissance over an 'intensive protection zone' south of the 52nd parallel, between 1996 and 2005, 2791 forest fires were started by lightning and burned 9608 km^2 of forest. Once again, lightning was responsible for starting 34% of the forest fires and burning 95% of the surface area (SOPFEU, 2006).

Since the early 1990s, the systematic detection of lightning on a continental scale has been made possible by lightning detection networks that use sensors deployed across North America; these count the number of lightning strokes and determine their intensity, polarity and the exact moment when the discharge produces an electromagnetic pulse. Using the data from these networks, studies were performed on a continental scale to describe the spatio-temporal patterns of the flashes. For example, Orville et al. (2002) presented results for all of North America for the period 1998 to 2000 and proved that in most of the United States, cloud-to-ground lightning density is greater than 1 lightning flash km^{-2} yr^{-1}. However, because of the relatively greater number of lightning strokes in the United States compared with Canada and because of the resolution of the maps, the Orville study does not show detailed patterns for Canada. For the same period (1998–2000), Burrows et al. (2002) carried out a similar study with data from the Canadian Lightning Detection Network (CLDN), which also includes cloud-to-cloud lightning. This study was the first to provide information on the general behaviour of lightning in Canada through the discovery of a complex national lightning pattern that shows strong regional, diurnal and seasonal correlations.

One of the characteristics of lightning is its polarity, which can be classified as either positive or negative. Thus far, very few studies have explored the spatio-temporal patterns of lightning polarity. Some authors suggest that the energetic nature of positive lightning and its ability to provide a sustained, continuous current could be the cause of many forest fires (Fuquay et al., 1972; Fuquay, 1982; Latham and Williams, 2001), and so investigation of these characteristics is important.

Using data covering a 10-year period (1996–2005) in southern Quebec, this study illustrates the spatial and temporal variations of lightning by analyzing the distribution of its density and the number of lightning days in a given time period. We also focus more closely on the phenomenon of lightning polarity. Given that so little has been published on lightning polarity, the comparative analysis will enable us to investigate this characteristic further. Also, despite the fact that the total number of lightning strokes in Quebec is relatively small on a North American scale, we will endeavour to characterize its behaviour on a provincial scale (Quebec) and produce quantitative values for spatial and temporal variations while also taking the polarity of the lightning into account.

2 Data and analyses

a *Study Area*

Geographically, the study area (45°–53°N; 65°–81°W) totals 1,032,382 km^2 (Fig. 1). It includes three of the fifteen Canadian ecozones: the boreal shield ecozone north of 46°N; the mixed-wood plains ecozone along the St. Lawrence Plain as far as Québec City; and the Atlantic maritime ecozone, which includes the eastern districts, the Gaspé Peninsula and New Brunswick. The entire study area has short, hot summers and cold, snowy winters. The Quebec section of the boreal shield ecozone is comprised of four ecoregions that are characterized by an average annual temperature of approximately 0°C and precipitation that varies between 650 and 1000 mm. Average annual temperature in the mixed-wood plains ecozone is 5°C and precipitation varies between 800 and 1000 mm annually. The Quebec section of the Atlantic maritime ecozone is located in the Appalachian Mountain range, which has an average annual temperature of 3.5°C and slightly higher precipitation (between 900 and 1300 mm) than the other zones. Average seasonal temperatures (May to August) are highest in the St. Lawrence Lowlands (16.5°C), followed by the Abitibi Plains, the Southern Laurentians and the Appalachians (14.0°C), and finally by the Rivière Rupert Plateau and the Central Laurentians (12.5°C) (Ecological Stratification Working Group, 1996).

b *Lightning Data*

The lightning data were provided by Hydro-Québec, which operates its own lightning detection network. Between 1994 and 2001, the lightning detection network used information from six sensors. Data were compared with Conférence Internationale de Grande Reseaux Electrique (CIGRE) lightning counters in order to overcome variations in detection efficiency over the province. Upgraded in 2001, the network is now comprised of 14 Lightning Positioning and Tracking

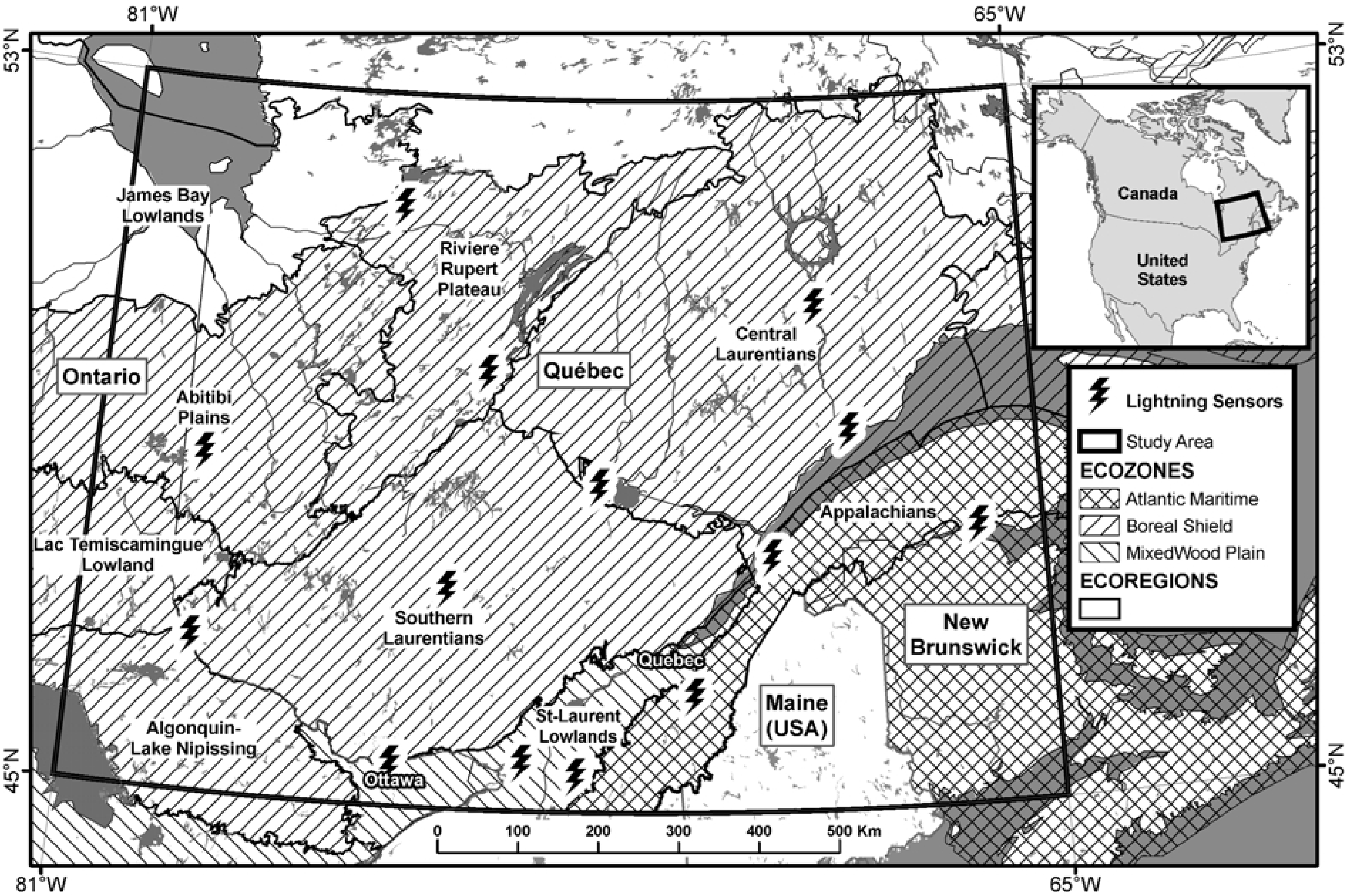

Fig. 1 Map of the study area showing the location of the actual (2001 - present) lightning sensors.

Sensors, Series 4 (LPATS-IV) that detect the exact hour at which radio pulses are generated by lightning. The efficiency and precision of the upgraded system varies between 80 and 90% at ±500 m for lightning flashes greater than 5 kA. The Hydro-Québec network specializes in the detection of cloud-to-ground lightning strokes. The observations available for our study were latitude, longitude (decimal degrees), date, time (UTC in the format hh:mm:ss.ddd; subtract 5 h from UTC to obtain Eastern Standard Time (EST)), and lightning polarity. The study covers the period from 1 May 1996 to 31 December 2005 and includes 3,834,665 lightning strokes. According to the manufacturer's specifications, the theoretical efficiency of lightning detection within the study zone decreases gradually from 90% at the centre (Lac St-Jean area) to 70% at the periphery (Fig. 2a). The theoretical precision of the location of the lightning strike also decreases from 0.5 km at the centre to 1 km at the periphery (Fig. 2b). The data are therefore less precise at the periphery of the area than at the centre. The lightning density results were not adjusted to account for the efficiency of the detection system, as was done in other studies (Orville, 1991, 1994; Livingston et al., 1996; Orville and Silver, 1997; Hodanish et al., 1997; Huffines and Orville, 1999; Boccippio et al., 2001). The network's detection sensors have improved in quality since 1995 and now have an efficiency greater than 80% (Cummins et al., 1998). As in the study performed by Orville and Huffines (1999), all of the peak currents are included in our analyses. In the study carried out by Cummins et al. (1998), the authors recommended eliminating positive peak currents of less than 10 kA, which could result from intracloud flashes. However, because only 1% of the lightning strokes reported by Hydro-Québec were affected by this phenomenon, we did not eliminate them from the database (Martin Vachon, personal communication, 2007).

c *Analysis of Temporal Patterns*

We first needed to determine if the total annual number of lightning strokes — polarity notwithstanding — was consistent from one year to the next between 1996 and 2005. Thus, we regulated the data using a standard normal distribution for *Z* variables. We applied a Bonferonni correction to take into account the fact that multiple comparisons were made. The distributions for annual, monthly and hourly frequencies were produced, and they accounted for the ratio of positive to negative strokes. In order to analyze the consistency of the ratio of positive to negative strokes for the various time scales, chi-square tests were used with SAS 9.1 software to compare the percentage values. Lastly, for each of the 10 years, the

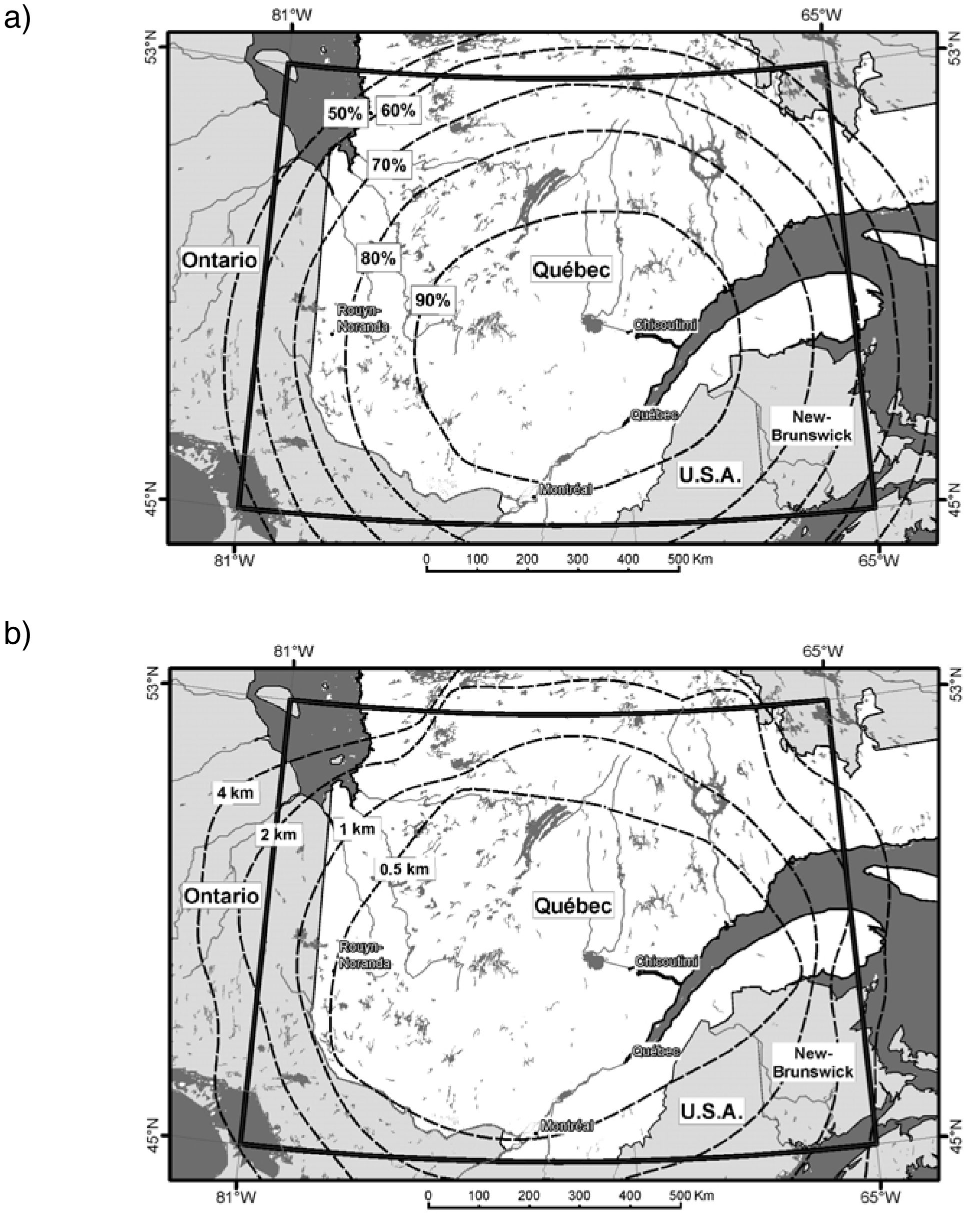

Fig. 2 Maps illustrating a) the theoretical effectiveness (detection efficiency, %) and b) the theoretical precision (location error, km) of the actual (2001-present) detection system.

number of days with at least one lightning stroke was also calculated, taking the polarity of the stroke into account.

d *Analysis of Spatial Patterns*

1 LIGHTNING STROKE DENSITY

In order to create a map that displays generalized spatial patterns that can be easily identified, lightning stroke density was calculated using the 'Density' function of the ESRI® ArcMap™ 9.1 software, which is used for spatial analysis. This function calculates the density of points surrounding each cell of an output matrix (GRID). The density calculation involves counting the total number of lightning strokes both within a predefined search radius and around a central cell of predetermined dimensions then dividing this number by the total surface area. In our study, we set the dimension of the output unit at 1 km^2 and the length of the search radius at 17,841 m, which is the radius required to obtain a circular area of 1000 km^2. Each of the cells of the resulting GRID has a density value that represents the number of points per square kilometre for 10 years. Also using ArcMap, we created a new GRID by dividing the values of each cell by 10 years to obtain the annual density values. Lastly, we classified this GRID into five categories according to Jenks' Natural Breaks method. Natural Breaks classification is a method of data classification that seeks to partition data into classes based on natural groups in the data distribution. The class breaks are determined statistically by finding adjacent feature pairs between which there is a relatively large difference in data value. Natural breaks occur in the histogram at the low points of valleys. Breaks are assigned in the order of size of the valleys, with the largest valley being assigned the first natural break. Jenks' optimization seeks to reduce variance within groups and maximize variance between groups (ESRI, 2005). To represent the interannual variation in lightning density spatially in the study area, we calculated the coefficient of variation of lightning density for the 10-year period for each cell of 63 km^2 (see Section 2d2) and categorized them using the Natural Breaks method (Jenks) into five categories.

2 Number of lightning days and proportion of positive lightning strokes

The study area was divided into 16,384 cells of 0.125° (7′30″) longitude by 0.0625° (3′45″) latitude and then projected using the Lambert Conformal Conic projection (North American Datum of 1983). In this projection system, the average surface area of a cell is 63 km^2 (approximately 9 km × 7 km), and it varies between 57.5 km^2 in the northern section of the study area and 68.7 km^2 in the southern section due to geographic distortion.

For each 63 km^2 cell, the fraction of positive lightning strokes was calculated by dividing the number of positive lightning strokes by the total number of lightning strokes. The number of lightning days was defined as the number of days per unit of time during which at least one lightning stroke was recorded in each cell. The polarity ratio was calculated using a summary compiled for each cell to determine the total number of positive and negative lightning strokes. We then performed a neighbourhood analysis on 32 km × 32 km (approximately 1024 km^2) using ESRI® ArcMap™ 9.1 software and categorized the results using the Natural Breaks method (Jenks).

3 Results

a *Temporal Patterns*

Generally speaking, although 2000, 2001, 2003 and 2005 appear to be different from the mean with regard to the total number of lightning strokes (Table 1 and Fig. 3), the difference in total lightning strokes for all of these years is not significant, even though 1996 is not represented in our database in its entirety (May to December only). Only 2005 had more than the average number of lightning strokes with a Z value of 1.77 (p=0.0384). Therefore, when applying a Bonferroni test for multiple comparisons, it is not significant. Of the 3,834,665 lightning strokes recorded in the database, 76.4% had negative polarity, with the minimum of 65.7% occurring in 2000 and the maximum of 81.5% occurring in 2005. The polarity ratio (negative:positive) of lightning strokes was also consistent from one year to the next (χ^2_{Obs}=10.42, degrees of freedom 9, p=0.3174), with a ratio of 76:24.

b *Annual Number of Lightning Days*

There was an average of 239 lightning days per year, with minimum and maximum values of 169 and 299 in 1997 and 2005, respectively (Table 1). The annual distribution indicates that the total number of lightning days is proportional to the total quantity of lightning strokes (Fig. 3). Furthermore, between 1996 and 2002, the number of days with at least one positive stroke was higher than the number of days with at least one negative stroke. This tendency reversed from 2003 until 2005, with a maximum of 289 days with negative strokes occurring in 2005. Figure 4 indicates that the lightning strokes were concentrated over a few days. Thus, on average, 50% of the total annual lightning was distributed over 11 days, 75% over 25 days and 90% over 44 days between 1996 and 2005. Note that when data for all years are combined, the maximum number of lighning strokes occurs on 15 July.

c *Monthly Distribution of Lightning Strokes*

Figure 5 shows the average monthly distribution of lightning strokes. The majority of lightning strokes occurred during June, July and August (27.2%, 39.1% and 21.0%, respectively). Only 12.7% of the total number of lightning strokes was observed during the remaining nine months of the year (during the fire off-season), i.e., from September to May. A more in-depth analysis of the monthly percentage of negative strokes to the total number of lightning strokes revealed significant differences between the November to March period and the April to October period (Fig. 5). Between October and November, the percentage of negative lightning strokes decreased from approximately 73 to 44% and remained around 50% for December and January. In February, the percentage of negative strokes reached a minimum of 13%. In March, this increased to 54% and remained stable around 77% from April to October (χ^2_{Obs}=1.8534, degrees of freedom 6, p=0.9327).

d *Hourly Distribution of Lightning Strokes*

The average number of lightning strokes per hour reached a minimum at about 14:00 UTC (Fig. 6). The number of strokes increased from 15:00 UTC onward, reaching a maximum at about 21:00 UTC, then decreased steadily until 5:00 UTC. Over a 9-hour period (6:00 UTC to 15:00 UTC), the average number of lightning strokes per hour remained stable and represented 16.9% of the total daily number. The remaining strokes (83.1%) occurred over a 15-hour period. The chi-square value (χ^2_{Obs}=6.8231, degrees of freedom 23, p=0.9996) reveals that the percentage of positive lightning strokes remained constant throughout the day, despite the slight tendency for the percentage of negative strokes to be below average during the period between 2:00 UTC and 8:00 UTC and higher than average between 20:00 UTC and 22:00 UTC (Fig. 6).

e *Analysis of Spatial Patterns*

1 Lightning stroke density

In general, lightning stroke density varies according to two increasing gradient axes (Fig. 7): north-south and east-west. The spatial distribution of the strokes reveals a higher density in the southern and western sections of the study area, with

TABLE 1. Annual number of negative and positive cloud-to-ground lightning strokes and lightning days for 1996 to 2005.

	Lightning strokes			Lightning days		
Years	(–)	(+)	Total (–,+)	(–)	(+)	Total (–,+)
1996	379 649	108 302	487 951	164	169	173
1997	289 950	84 220	374 170	152	167	169
1998	348 702	121 682	470 384	214	225	238
1999	304 706	118 624	423 330	209	243	250
2000	154 500	80 605	235 105	182	197	202
2001	206 357	60 943	267 300	241	273	283
2002	286 658	78 900	365 558	243	250	279
2003	174 716	64 109	238 825	240	227	263
2004	325 184	81 288	406 472	223	173	231
2005	460 764	104 806	565 570	289	200	299
Sum	2 931 186	903 479	3 834 665			
Ave	293 119	90 348	383 467	216	212	239
STD	94 668	21 632	110 848	41	37	45

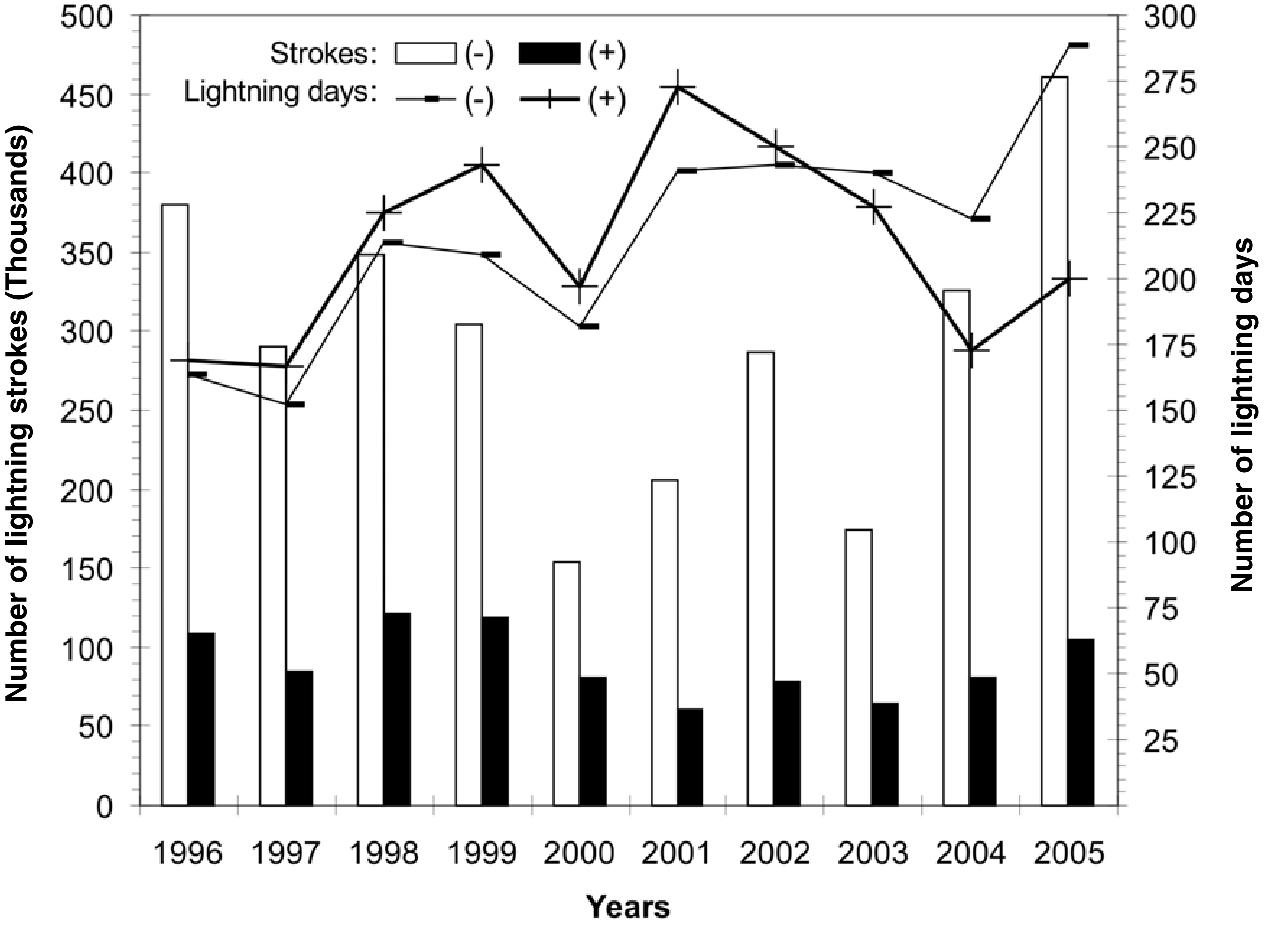

Fig. 3 Distribution of the annual number of negative and positive cloud-to-ground lightning strokes and lightning days for 1996 to 2005. The bars (left axis) show the number of lightning strokes and the lines (right axis) show the number of lightning days.

an average of 0.52 to 1.27 lightning strokes km^{-2} yr^{-1}. The St. Lawrence Lowlands ecoregion received the greatest number of lightning strokes annually (between 0.73 and 1.27 lightning strokes km^{-2} yr^{-1}). Three ‘regions’ of approximately 15,000 km^2 clearly stand out with values greater than 0.73 lightning strokes km^{-2} yr^{-1}. These are 1) the Ottawa region, which runs eastward along the south shore of the Ottawa River to Montréal and north to Maniwaki; 2) a larger region from Montréal to Québec City, which lies on both sides of the St. Lawrence River over a distance of 75 to

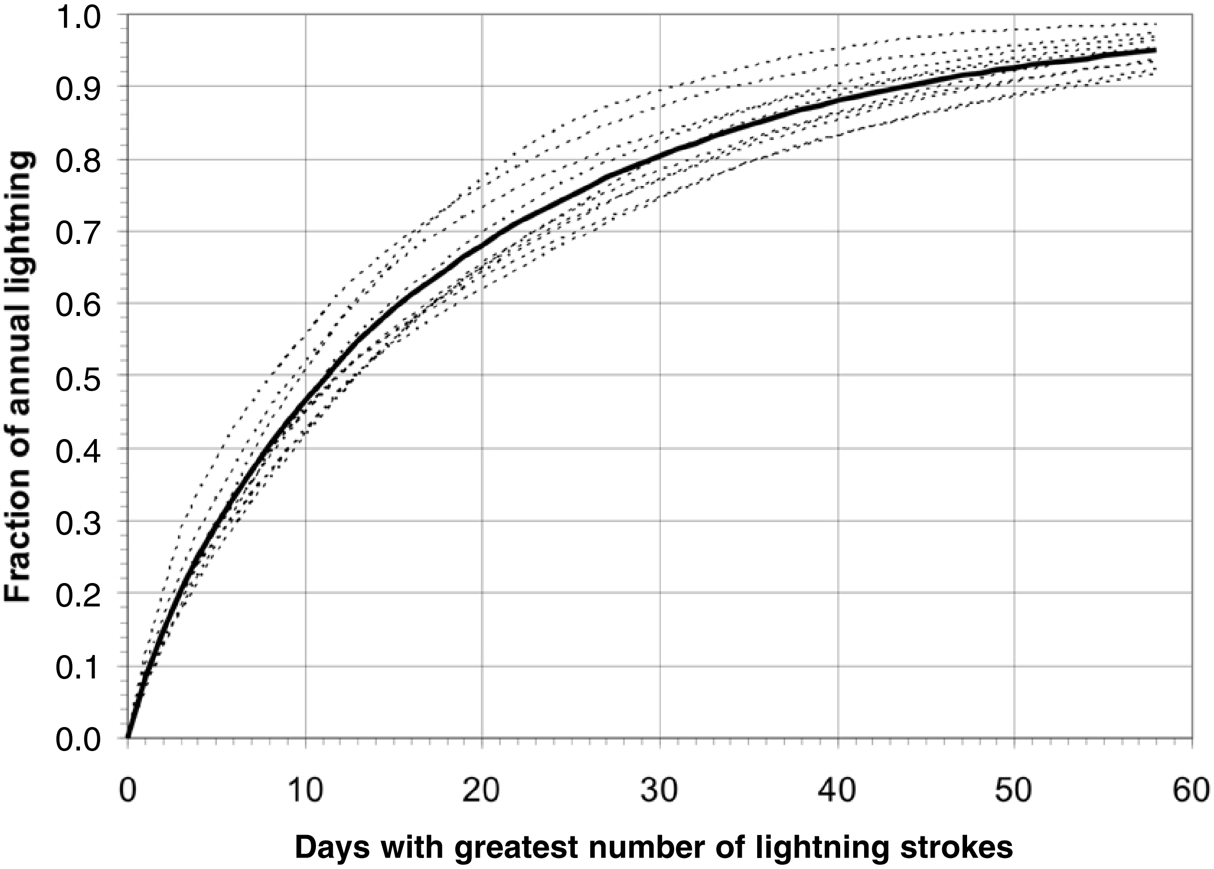

Fig. 4 Fraction of total annual cloud-to-ground lightning strokes for the days with the greatest amount of lightning for 1996 to 2005. The solid line shows the mean and the dashed lines show the ten individual years.

100 km inland; and 3) along the Quebec border between northwestern New Brunswick (Canada) and the state of Maine (U.S.). Another high-density region that is more fragmented is located in Abitibi, west of the Gouin Reservoir. The region with the lowest recorded densities is located in the northeastern section of the study area, with an average annual number of lightning strokes less than 0.33 km^{-2} yr^{-1}. It is interesting to note that the central section of the study area, just west of Lac St-Jean, has a rather low density with values between 0.16 and 0.33 lightning strokes km^{-2} yr^{-1}. A greater interannual variation is observed where lightning density is the lowest (Fig. 8), thus showing a reverse pattern to that of Fig. 7. The greatest variations are observed in the northeast of the study area.

2 NUMBER OF LIGHTNING DAYS AND PERCENTAGE OF POSITIVE LIGHTNING STROKES

Figure 9 shows the spatial distribution of the mean number of lightning days per year per 63 km^2 cell for 1996 to 2005; the general trends observed in Fig. 7 (density) are about the same. The same two gradient axes can be observed crossing from north to south and from east to west. However, the spatial patterns observed are much more distinct, and the regions are more homogeneous and contiguous than those analyzed for density. The ecoregion with the greatest number of lightning days per year per 63 km^2 cell remains the St. Lawrence Lowlands with 8.5 to 13.0 days. The western half of the Southern Laurentians ecoregion has the same intensity. It is followed by the Abitibi Plains ecoregion and the southern section of the Rivière Rupert Plateau ecoregion, with 6.7 to 8.4 days each. The values for the rest of the area decrease from 6.6 days of lightning in the southeastern section to only 1.0 day in the northeastern section of the North Shore region, from Baie-Comeau (49°13’N; 68°12’W) northward and eastward.

Figure 10 shows the spatial distribution of the percentage of positive lightning strokes. It varies considerably in the area, ranging from 0 to 65%, depending on the location. The northern half of the Rivière Rupert Plateau ecoregion and the coastal section of the Central Laurentians (North Shore) are the areas where the percentage of positive lightning strokes is the highest, with 31 to 65% positive strokes. For the rest of the region, this ranges between 0 and 30%, which is within average values. Note that while the St. Lawrence Lowlands ecoregion has the highest density and number of lightning days, it has the lowest number of positive strokes.

4 Discussion

a *Temporal Variations*

Although lightning is present throughout the year in Quebec, we have seen that it is more concentrated during certain periods of time, with half of the total annual lightning occurring

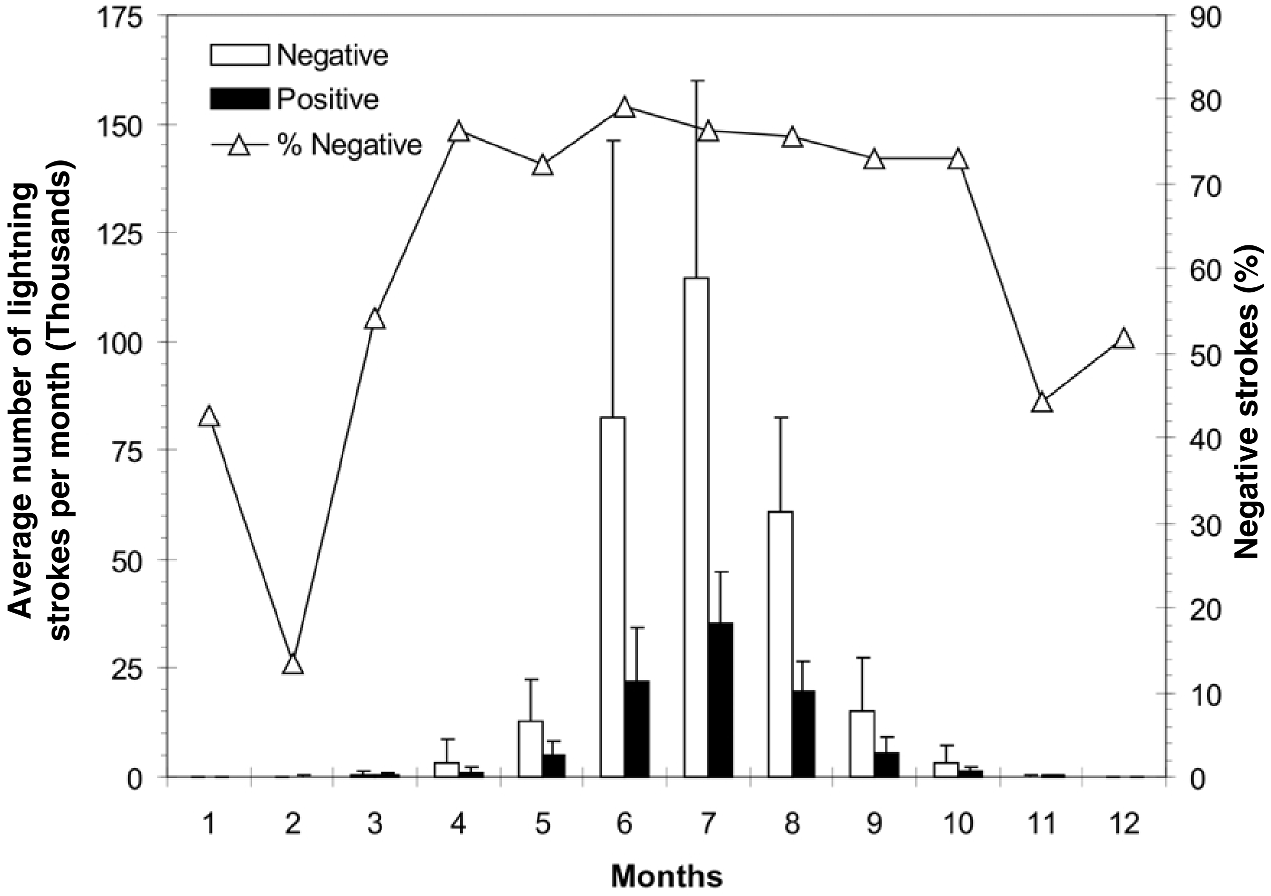

Fig. 5 Mean monthly stroke counts (1996–2005). The bars (left axis) show the average number of monthly lightning strokes (±1 standard deviation). The line (right axis) represents the monthly percentage of negative strokes.

over 11 days and nearly all of it (90%) over only 44 days. By comparison, the cumulative distribution of lightning between 1995 and 1999 indicates that approximately 10% of the days with lightning accounted for 50% of the lightning production throughout the contiguous United States (Zajac and Rutledge, 2001). The fact that the days with the greatest number of lightning strokes are concentrated in the summer months may explain why 1996, which has missing data from January to April, does not differ from the mean number of lightning strokes of other years.

On a monthly basis, the study of lightning distribution according to polarity has shown that there is a greater number of positive strokes than negative strokes between November and March. Orville et al. (1987) reported similar results in their study of lightning characteristics for the northeastern United States from 1984 to 1985. Once again, the number of positive strokes was greater than 50% from December to March. The maximum number of positive strokes (80%) occurred in February; during the summer it was less than 5%. Positive lightning represents approximately 10% of the total lightning recorded in the world, and its physical origins are still unknown (Latham and Williams, 2001). Zajac and Rutledge (2001) reported the same percentage in a study of the spatio-temporal aspects of lightning in the United States between 1995 and 1999. Our results concur with those of a recent study conducted by Sonnadara et al. (2006) on the characteristics of cloud-to-ground lightning in Sweden. During the period 1987–2000, no visible trends in the percentage of positive flashes or the total number of flashes were detected. Moreover, their study revealed large variations in the mean monthly percentage of positive flashes, with the lowest values occurring in July and the highest in January. The results of Sonnadara et al. (2006) once again confirm that the percentage of positive strokes has a strong seasonal dependence with a higher percentage during winter thunderstorms compared with summer thunderstorms.

With regard to the seasonal variation in polarity ratio, our results concur with published observations. Clodman and Chisholm (1996) found that the amount of positive lightning is greater during spring and fall than during summer and that it also varies according to latitude, being greater in the north than in the south and greater during the night than during the day. Moreover, Orville et al. (1987), Orville and Silver (1997), Orville and Huffines (1999) and Bentley and Stallins (2005) observed that positive lightning flashes clearly occur more frequently during winter. As summarized by Bentley and Stallins (2005), the significant difference in the percentage of positive lightning between winter and summer was

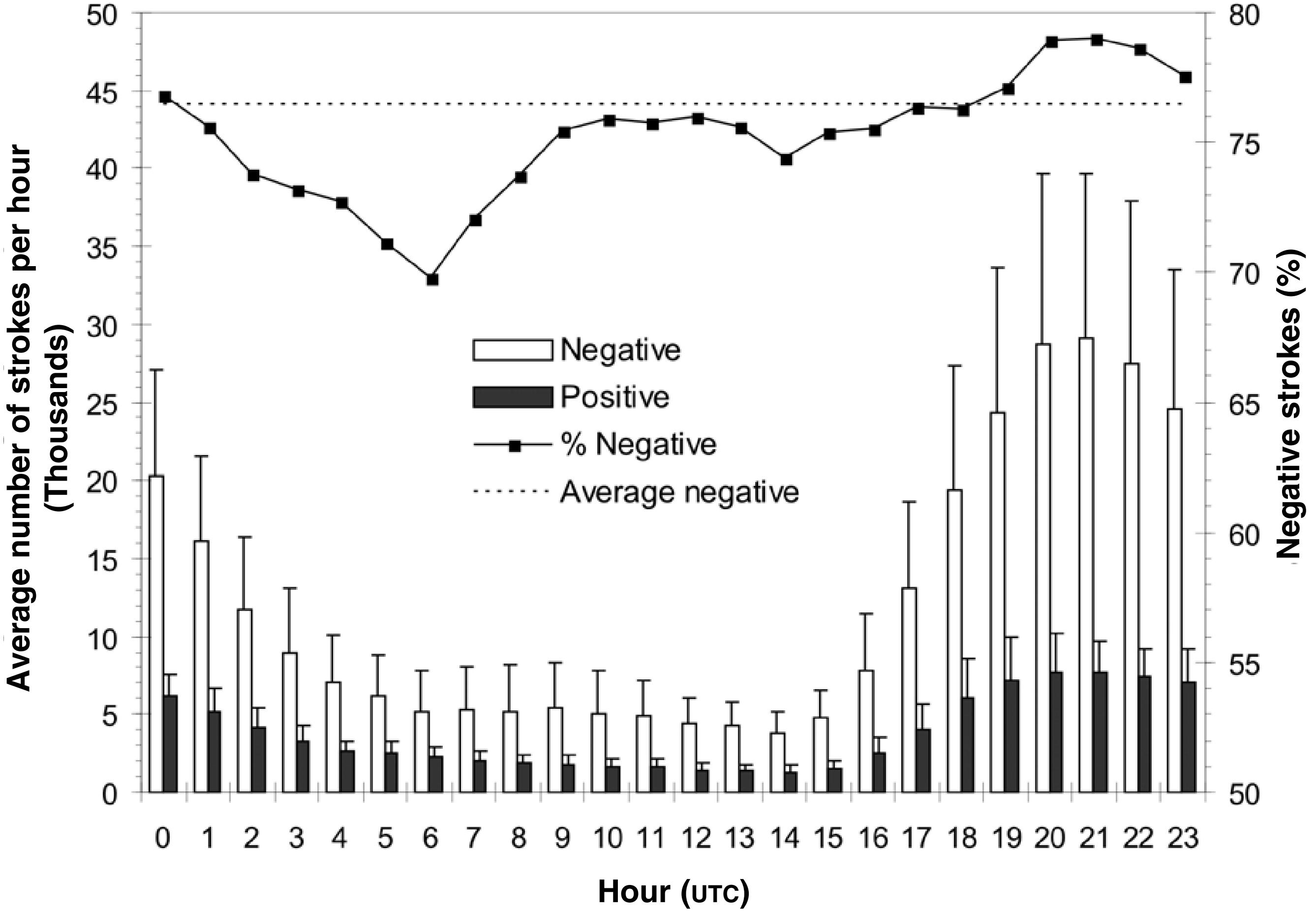

Fig. 6 Mean diurnal (UTC) stroke counts. The bars (left axis) show the average number of strokes per hour (±1 standard deviation). The solid line (right axis) represents the hourly percentage of negative strokes. The dashed line represents the annual mean. Note: the right axis starts at 50%.

first identified by Orville and Songster (1987) and further explored by Orville and Huffines (1999). Engholm et al. (1990) attributed the behaviour of positive lightning during the winter to increased vertical wind shear (i.e., tilted dipole) and lower cloud tops during this season.

Despite the fact that the annual number of negative strokes was greater than the number of positive strokes by a ratio of 76:24, and that this relationship was consistent from one year to the next, the number of days with at least one positive stroke was greater than the number of days with at least one negative stroke for the period 1996–2002. The opposite was observed from 2003 to 2005.

If we examine the distribution on a diurnal basis, we observe the same trend: positive strokes occurred more often during the time of day when the temperature was cooler. Flannigan and Wotton (1991) observed the same variations based on the time of day for the Ontario fire season (15 April to 21 September 1998), but with a lower percentage of positive strokes (3 to 10% for Ontario, compared with 20 to 30% for Quebec). They also obtained two peaks in the percentage of positive lightning: one at 8:00 UTC and a second at 14:00 UTC. In the Quebec study, a first peak is clearly observed earlier at 6:00 UTC, with a second smaller peak at 14:00 UTC.

b *Spatial Variations*

Our results show significant spatial heterogeneity with regard to density, the number of lightning days and percentage of positive lightning strokes. This heterogeneity is expressed by gradients with significant longitudinal and latitudinal variations. In Quebec, the convergence of cold dry air masses from the north with hot humid air masses from the south is clearly conducive to the development of thunderstorms. However, as several studies have suggested, other factors such as topography may play a role in the high density of lightning in the St. Lawrence Lowlands ecoregion. Orville and Huffines (2001) suggest that the longitudinal variation of lightning density observed in the United States could be primarily related to topography. They based this assumption on the findings of Reap (1986), who demonstrated that lightning activity increased with the elevation of the land, from sea level to nearly 3000 m.

The geographic distribution of the percentage of positive lightning strokes appears to be the reverse of lightning density or the number of lightning days. Orville and Huffines (2001) also observed a similar pattern on a continental scale (North America). However, the reverse relationship they observed was between the average annual density of positive

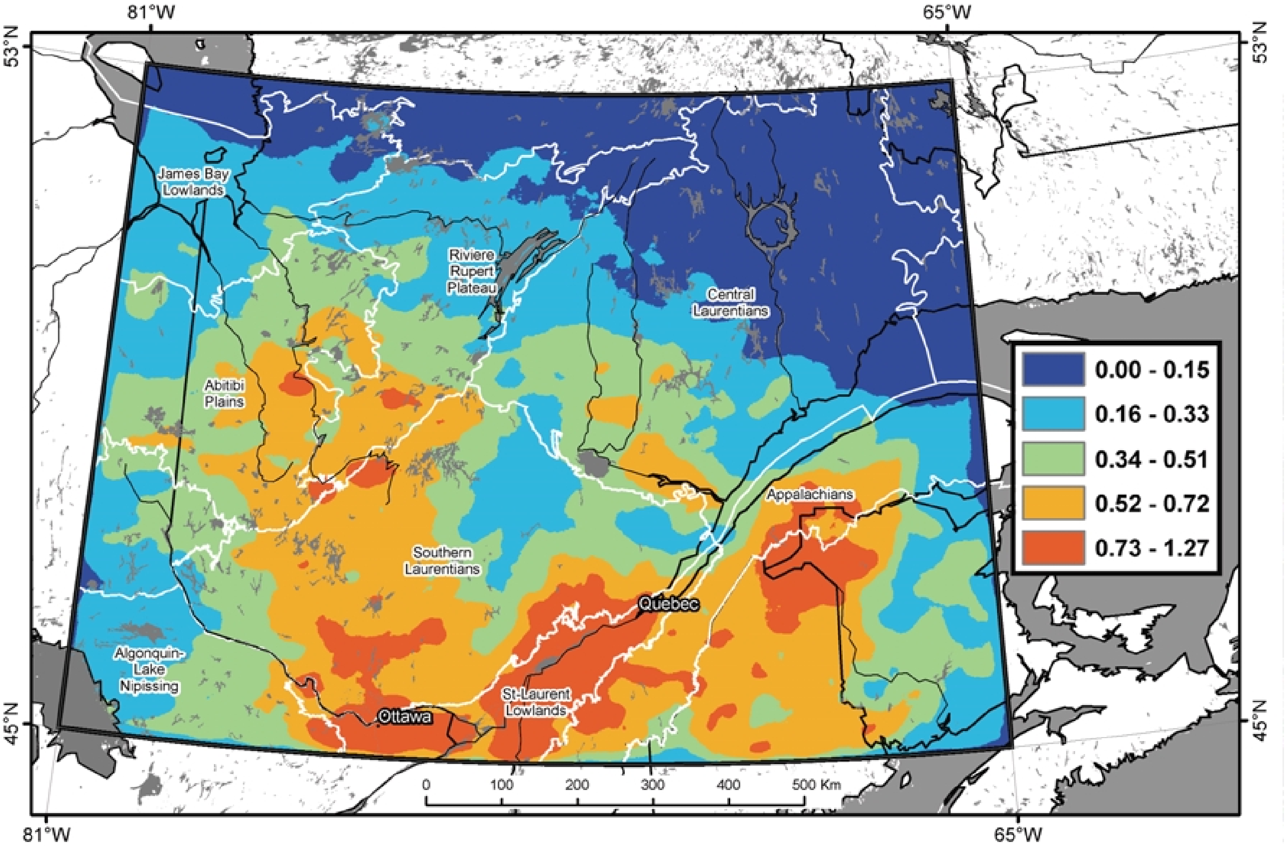

Fig. 7 Mean annual cloud-to-ground lightning stroke density (total number km^{-2} yr^{-1}) for 1996 to 2005. Natural breaks in five classes.

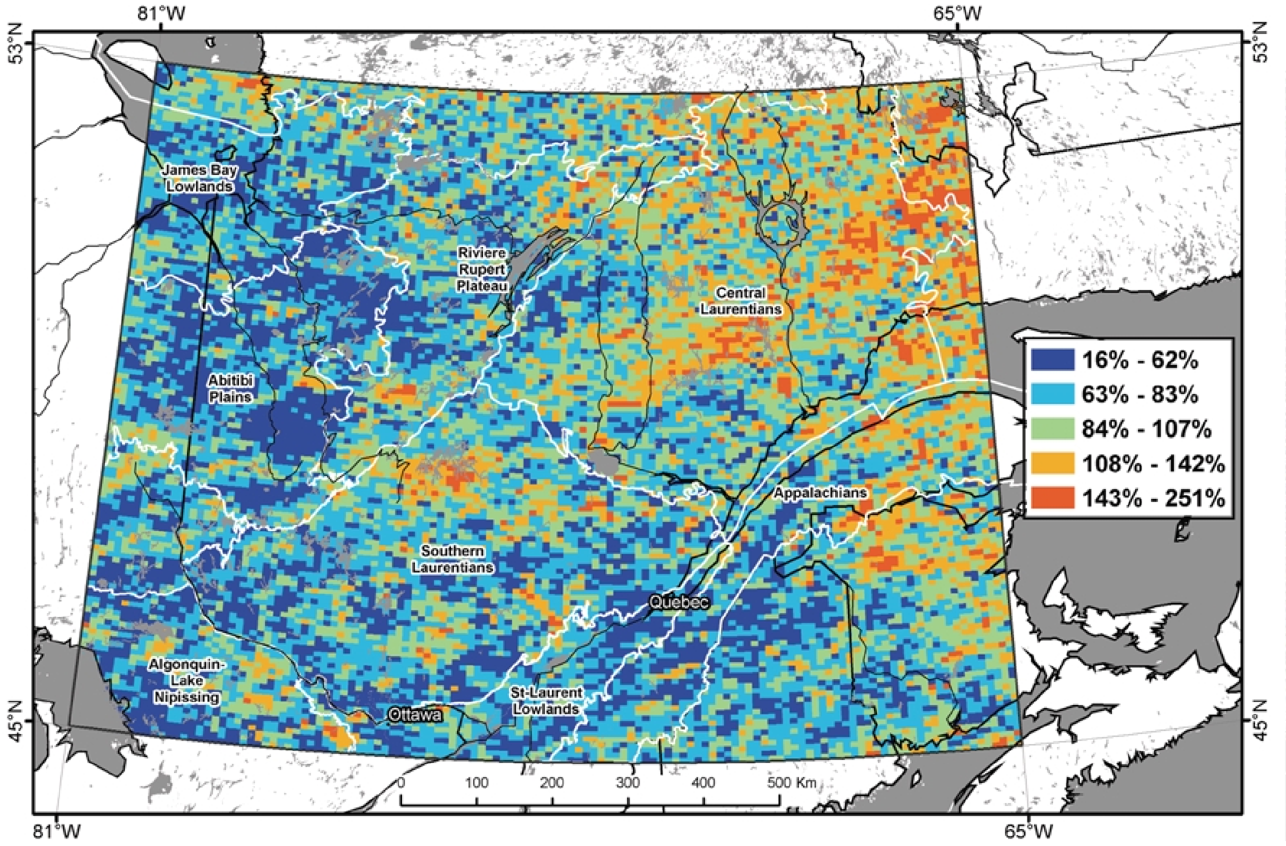

Fig. 8 Annual coefficient of variation (%) of total lightning stroke numbers for 1996 to 2005. Cells are 63 km^2. Natural breaks in five classes.

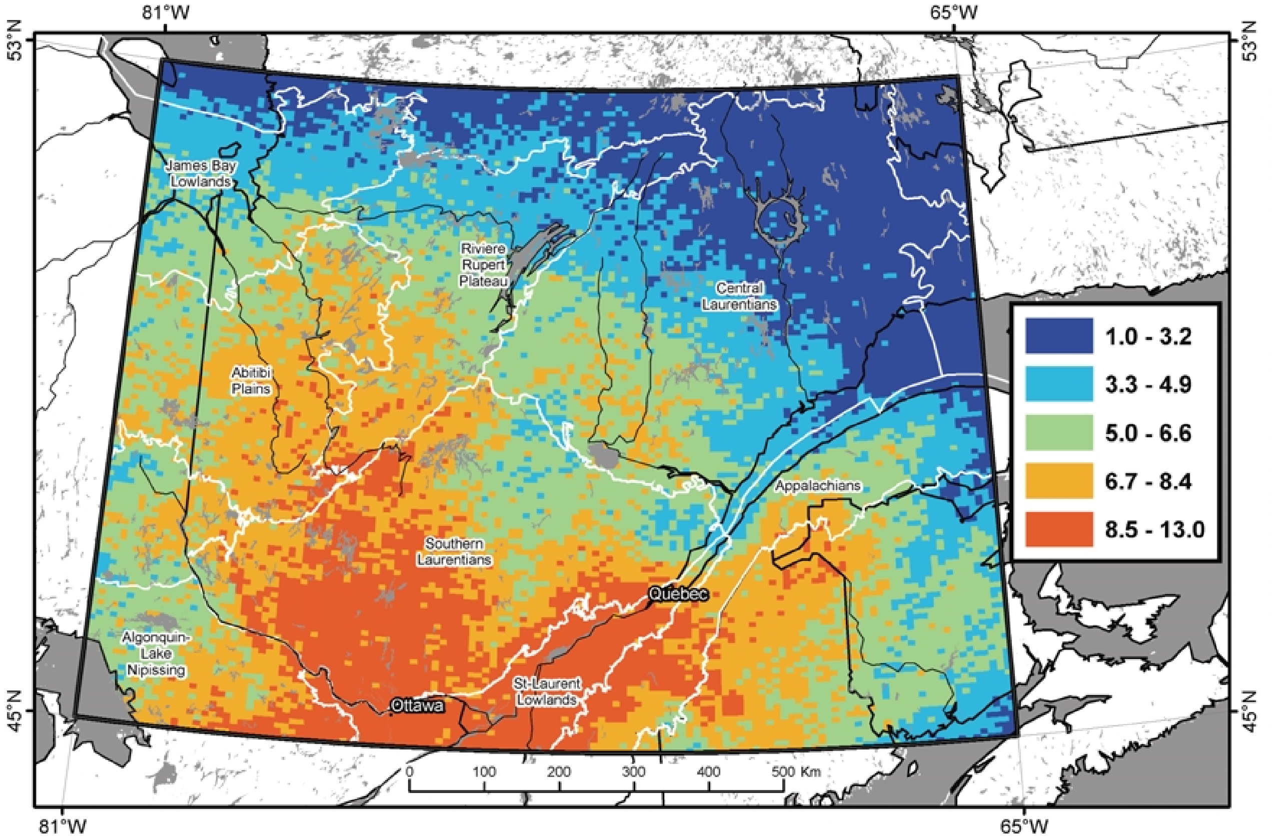

Fig. 9 Mean number of lightning days per year per 63 km^2 cell for 1996 to 2005. Natural breaks in five classes.

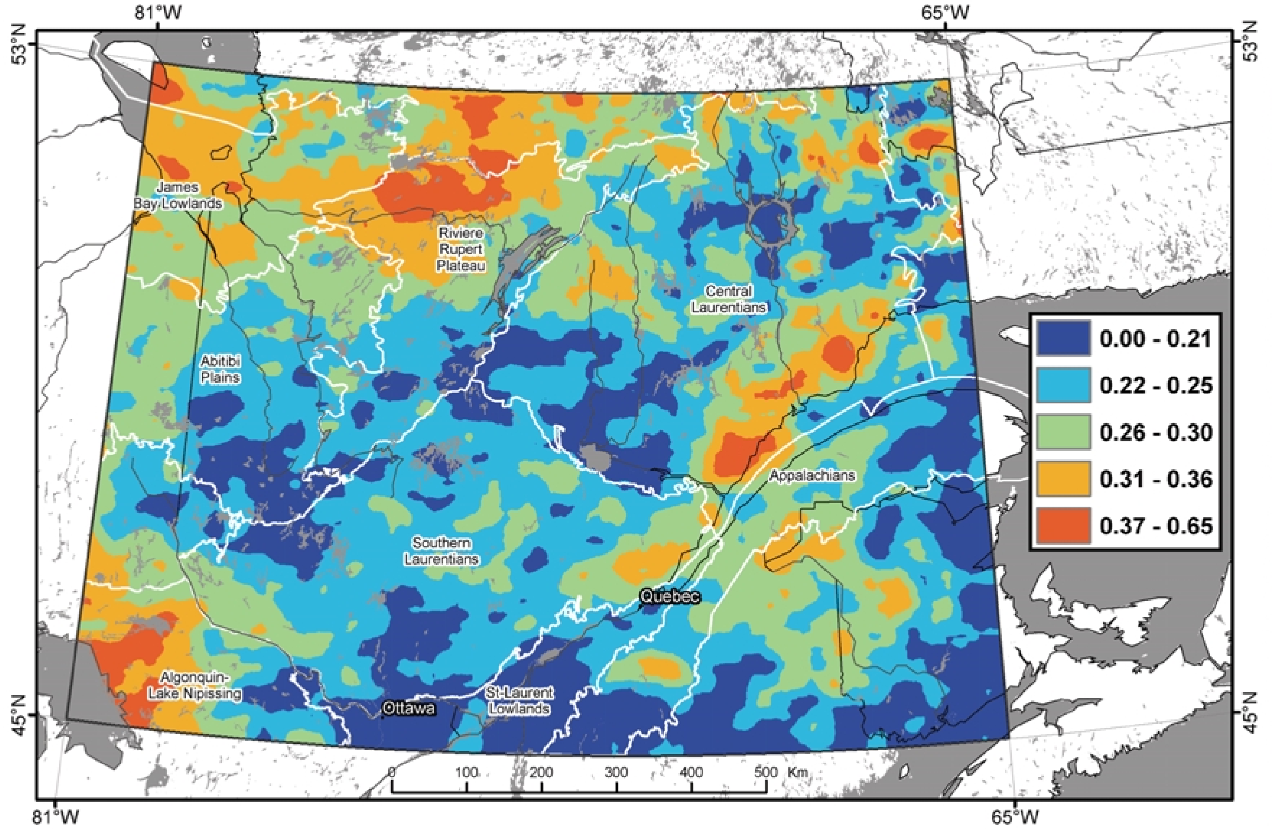

Fig. 10 Fraction of positive lightning strokes for 1996 to 2005. Neighbourhood analysis on 32 km × 32 km (approximately 1024 km^2). Natural breaks in five classes.

flashes and the average positive peak current. When they examined the spatial distribution of the percentage of positive lightning alone, the geographical distribution varied considerably in latitude and longitude. On a North American scale, Orville et al. (2002) also observed more positive lightning, greater than 20%, in British Columbia, the western Yukon, Quebec, Labrador and eastern Newfoundland. At the time, they attributed the elevated number of positive lightning strokes to differences between the Canadian and US networks and to the fact that the Canadian Lightning Detection Network was relatively new. Our results for Quebec indicate that their observations were probably not an artefact of the system as, on average, 25% of the lightning strokes in southern Quebec between 1996 and 2005 were positive. The values for northern Quebec and the North Shore were between 25 and 65%. Once again, our results are similar to the findings of Sonnadara et al. (2006) who observed that in southern Sweden the percentage of positive lightning is 10%, while in the northern regions this percentage varies from 20 to 100%.

Additional research must be done to establish connections between our results and environmental variables such as topography and vegetation, as well as the spatial variations of lightning and instances of fire.

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References

BENTLEY, M.L. and J.A. STALLINS. 2005. Climatology of cloud-to-ground lightning in Georgia, USA, 1992–2003. *Int. J. Climatol.* **25**(15): 1979–1996.

BOCCIPPIO, D.J.; K.L. CUMMINS, H.J. CHRISTIAN and S.J. GOODMAN. 2001. Combined satellite- and surface-based estimation of the intracloud-cloud-to-ground lightning ratio over the continental United States. *Mon. Weather Rev.* **129**(1): 108–122.

BURROWS, W.R.; P. KING, P.J. LEWIS, B. KOCHTUBAJDA, B. SNYDER and V. TURCOTTE. 2002. Lightning occurrence patterns over Canada and adjacent United States from Lightning Detection Network observations. ATMOSPHERE-OCEAN, **40**(1): 59–81.

CLODMAN, S. and W. CHISHLOM. 1996. Lightning flash climatology in the southern Great Lakes region. ATMOSPHERE-OCEAN, **34**(2): 345–377.

CUMMINS, K.L.; M.J. MURPHY, E.A. BARDO, W.L. HISCOX, R.B. PYLE and A.E. PIFER. 1998. A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network. *J. Geophys. Res.* **103**(D8): 9035–9044.

ECOLOGICAL STRATIFICATION WORKING GROUP. 1996. A National Ecological Framework for Canada. Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research, and Environment Canada, State of Environment Directorate, Ottawa/Hull. 125 pp. Map at scale 1:7.5 million. http://www.ec.gc.ca/soer-ree/English/Framework/default.cfm.

ENGHOLM, C.D.; E.R. WILLIAMS and R.M. DOLE. 1990. Meteorological and electrical conditions associated with positive cloud-to-ground lightning. *Mon. Weather Rev.* **118**(2): 470–487.

ENVIRONMENT CANADA. 2003. Backgrounder – Lightning activity across Canada. http://www.msc.ec.gc.ca/education/lightning/background_e.html.

FLANNIGAN, M.D. and B.M. WOTTON. 1991. Lightning-ignited forest fires in northwestern Ontario. *Can. J. Forest Res.* **21**(3): 277–287.

FUQUAY, D.M. 1982. Positive cloud-to-ground lightning in summer thunderstorms. *J. Geophys. Res.* **87**(C9): 7131–7140.

FUQUAY, D.M.; A.R. TAYLOR, R.G. HAWE and C.W. SCHMID JR. 1972. Lightning discharges that caused forest fires. *J. Geophys. Res.* **77**(12): 2156–2158.

HODANISH, S.; D. SHARP, W. COLLINS, C. PAXTON and R.E. ORVILLE. 1997. A 10-yr monthly lightning climatology of Florida: 1986–95. *Weather Fcstg.* **12**(3): 439–448.

HUFFINES, G.R. and R.E. ORVILLE. 1999. Lightning ground flash density and thunderstorm duration in the continental United States: 1989–96. *J. Appl. Meteorol.* **38**(7): 1013–1019.

LATHAM, D. and E. WILLIAMS. 2001. Lightning and forest fires. In: *Forest Fires: Behavior and Ecological Effects.* E.A. Johnson and K. Miyanishi (Eds), San Diego: Academic Press. pp. 375–418.

LIVINGSTON, E.S.; J.W. NIELSEN-GAMMON and R.E. ORVILLE. 1996. A climatology, synoptic assessment, and thermodynamic evaluation for cloud-to-ground lightning in Georgia: A study for the 1996 Summer Olympics. *Bull. Am. Meteorol. Soc.* **77**(7): 1483–1495.

ORVILLE, R.E. 1991. Lightning ground flash density in the contiguous United States—1989. *Mon. Weather Rev.* **119**(2): 573–577.

ORVILLE, R.E. 1994. Cloud-to-ground lightning flash characteristics in the contiguous United States: 1989–1991. *J. Geophys. Res.* **99**(D5): 10833–10842.

ORVILLE, R.E. and H. SONGSTER. 1987. The East Coast lightning detection network. *IEEE Trans. Power Deliv.* **PWRD-2**(3): 899–907.

ORVILLE, R.E.; R.A. WEISMAN, R.B. PYLE, R.W. HENDERSON and R.E. ORVILLE JR. 1987. Cloud-to-ground lightning flash characteristics from June 1984 through May 1985. *J. Geophys. Res.* **92**(D5): 5640–5644.

ORVILLE, R.E. and A.C. SILVER. 1997. Lighting ground flash density in the contiguous United States: 1992–95. *Mon. Weather Rev.* **125**(4): 631–638.

ORVILLE, R.E. and G.R. HUFFINES. 1999. Lightning ground flash measurements over the contiguous United States: 1995–97. *Mon. Weather Rev.* **127**(11): 2693–2703.

ORVILLE, R.E. and G.R. HUFFINES. 2001. Cloud-to-ground lightning in the United States: NLDN results in the first decade: 1989–98. *Mon. Weather Rev.* **129**(5): 1179–1193.

ORVILLE, R.E.; G.R. HUFFINES, W.R. BURROWS, R.L. HOLLE and K.L. CUMMINS. 2002. The North American Lightning Detection Network (NALDN)–first results: 1998–2000. *Mon. Weather Rev.* **130**(8): 2098–2109.

REAP, R.M. 1986. Evaluation of cloud-to-ground lightning data from the western United States for the 1983–84 summer seasons. *J. Appl. Meteorol.* **25**(6): 785–799.

SONNADARA, U.; V. COORAY and T. GÖTSCHL. 2006. Characteristics of cloud-to-ground lightning flashes over Sweden. *Physica Scripta*, **74**(5): 541–548.

SOPFEU. 2006. Tableau des statistiques de feux par année et par cause. http://www.sopfeu.qc.ca/html/francais/tour/stats_anneeCause.php

STOCKS, B.J. 1991. The extent and impact of forest fires in northern circumpolar countries. In: *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications.* J.S. Levine (Ed.), MIT Press, Cambridge, Mass. pp. 197–202

ZAJAC, B.A. and S.A. RUTLEDGE. 2001. Cloud-to-ground lightning activity in the contiguous United States from 1995 to 1999. *Mon. Weather Rev.* **129**(5): 999–1019.