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# A performance assessment of the World Wide Lightning Location Network (WWLLN) via comparison with the Canadian Lightning Detection Network (CLDN)

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## Abstract

The World Wide Lightning Location Network (WWLLN) uses globally-distributed Very Low Frequency (VLF) receivers in order to observe lightning around the globe. Its objective is to locate as many global strokes as possible, with high temporal and spatial (<10 km) accuracy. Since detection is done in the VLF range, signals from high peak current lightning strokes are able to propagate up to ∼$10^4$ km before being detected by the WWLLN sensors, allowing for receiving stations to be sparsely spaced.

Through a comparison with measurements made by the Canadian Lightning Detection Network (CLDN) between May and August 2008 over a 4° latitude by 4° longitude region centered on Toronto, Canada, this study found that WWLLN detection was most sensitive to high peak current lightning strokes. Events were considered shared between the two networks if they fell within 0.5 ms of each other. Using this criterion, 19 128 WWLLN strokes (analyzed using the Stroke_B algorithm) were shared with CLDN lightning strokes, producing a detection efficiency of 2.8%. The peak current threshold for WWLLN detection is found to be ∼20 kA, with the detection efficiency increasing to ∼70% at peak currents of ±120 kA. The detection efficiency is seen to have a clear diurnal dependence, with a higher detection efficiency at local midnight than at local noon; this is attributed to the difference in the thickness of the ionospheric D-region between night and day. The mean time difference (WWLLN – CLDN) between shared events was −6.44 µs with a standard deviation of 35 µs, and the mean absolute location accuracy was 7.24 km with a standard deviation of 6.34 km. These results are generally consistent with previous comparison studies of the WWLLN with other regional networks around the world. Additional receiver stations are continuously being added to the network, acting to improve this detection efficiency.

## 1 Introduction

There are many regional lightning detection networks operating around the world, providing data for purposes as varied as the prevention of lightning damage to sensitive equipment, the early detection of forest fires, and the tracking of local severe weather. They are used frequently for aviation operations, shipping routes, safety applications, and by sporting groups. Moreover, they are also employed by the insurance industry and electric utilities for insurance claims investigations and detecting power line fault locations (Cummins et al., 1998a). Meteorological agencies and research institutions use the data for studies dealing with indicators of climate change through seasonally and yearly averaged statistics (Williams, 1992; Schlegel et al., 2001; Price, 2009), studies dealing with the role lightning plays in determining atmospheric composition (e.g., Volland, 1984; Choi et al., 2005; Sioris et al., 2007; Martin et al., 2007), and for a priori information in weather forecasting models.

Although such regional lightning detection networks exist in many parts of the world and provide real-time data (e.g., Cummins et al., 1998b; Burrows et al., 2002; Lay et al., 2004; Rodger et al., 2005, 2006; Jacobson et al., 2006; Cummins and Murphy, 2009; Höller et al., 2009; Lagouvardos et al., 2009), they generally provide limited spatial coverage, typically ending near national boundaries, and are unable to provide lightning data over the ocean. Lightning detection instruments also exist on orbiting satellites, such as the Optical Transient Detector (OTD; Christian et al., 2003) and the Lightning Imaging Sensor (LIS; Mach et al., 2007), however they are not able to provide continuous global coverage for all points on the Earth's surface. The need for a genuinely world-wide, ground-based network is therefore undeniable, particularly for the coverage of the oceans and regions of low population density or economic development.

The World Wide Lightning Location Network (WWLLN) is such a network, and has been operational since March 2003. It is a low-cost, real-time, ground-based network that is capable of detecting lightning anywhere on the globe with high temporal and spatial accuracy. In this study, the WWLLN performance is evaluated over a region in Ontario, Canada by comparing it to the Canadian Lightning Detection Network (CLDN), a national network established in 1998. This is the first comparison between the WWLLN and the CLDN.

## 2 Lightning detection by the CLDN and the WWLLN

The CLDN and the WWLLN have somewhat similar detection methods, however, due to the difference in the sensors and spectral bands employed, they have contrasting detection ranges, network location accuracy, and detection efficiency ratings.

### 2.1 Description of the CLDN

CLDN was designed in 1997, and has been operated and managed by Environment Canada (EC) since 1998 (Dockendorff and Spring, 2005). It operates with line-of-sight detection of the ground wave, and only uses the first few microseconds of a lightning stroke in order to avoid interference with the sky wave produced from the same lightning event. The sensors of this network therefore operate in the Low Frequency (LF) band where attenuation is relatively high compared to the Very Low Frequency (VLF) band used for sky wave detection, and as a result, the receivers must be placed a few hundred kilometers apart.

The objective of the CLDN was to provide a cloud-to-ground flash detection efficiency of better than 90% and less than 500 m location accuracy in its region of coverage (Dockendorff and Spring, 2005). This goal has been achieved, and in order to do this, the network functions with 83 sensors distributed across the country, employing both Magnetic Direction Finding (MDF) and Time of Arrival (TOA) technologies; as of August 2009, it was composed of 27 IMPACT-ES, 30 LPATS-IV, 25 LS7000, and 1 LS7001 Vaisala sensors (Steve Kowalczyk, personal communication, 2009). The Lightning Position and Tracking System (LPATS) sensors use TOA, and the Improved Accuracy from Combined Technology (IMPACT) and CG (cloud-to-ground) Enhanced

Lightning Sensors (LS7000/LS7001) both use TOA and MDF for lightning detection (Cummins et al., 1998b; Rakov and Uman, 2003). At the start of the period of interest for this paper (May 2008), the CLDN configuration was somewhat different. The CLDN was composed of 27 IMPACT-ES, 40 LPATS-IV, and 16 LS7000 sensors, and during the campaign period (May to August 2008), four of the LPATS-IV sensors were upgraded to LS7000 sensors (Steve Kowalczyk, personal communication, 2009). Similar upgrades have continued at CLDN sites since then. Figure 1 shows the configuration of the CLDN during the acquisition of the data used in this work.

### 2.2 Description of the WWLLN

The WWLLN is a real-time, world-wide, ground-based network operated by the University of Washington that can detect strong lightning events occurring anywhere in the world. The network was initiated with the intention of achieving global detection with a location accuracy of less than 10 km (Rodger et al., 2009). The WWLLN receivers operate in the VLF band and detect the lightning wave packet that propagates in the region between the Earth and the lower ionosphere, termed the Earth-Ionosphere Waveguide (EIWG). These wave packets propagate in particular waveguide modes (TE, TM or TEM), which effectively obscure the polarity of the parent lightning strokes. However, the VLF energy radiated is directly related to the peak current, and WWLLN expects to be able to report the energy per stroke by the end of 2010.

The signal is a wave train, called a sferic, that rises slowly from the noise background and lasts for roughly a millisecond or more. This complicates the detection of the sferic, for which instead of the trigger time of the signal being used to locate lightning, the Time of Group Arrival (TOGA) is employed, along with minimization methods comparable to those used in the TOA method. Details of the TOGA method, as well as updates to the algorithms and waveform criteria, are discussed in detail by Dowden et al. (2002) and Rodger et al. (2009). In this work, data processed with the new Stroke_B algorithm were used; Rodger et al. (2009) show that this algorithm improves the WWLLN stroke count globally by 63%, and in some local regions by more than this.

In order to determine lightning locations, sky wave detection takes advantage of the higher spectral power density and lower attenuation available in the VLF range than in higher frequency bands, enabling the receivers to be placed several thousands of kilometers apart (Crombie, 1964). By comparing the WWLLN Darwin receiver's detected strokes against that of the WWLLN as a whole, Rodger et al. (2006) found that the detection efficiency of the sensor in the daytime decreases gradually with distance beyond ∼8000 km and is negligible after ∼14 000 km. At night, each sensor detects out to about 10 000 to 12 000 km with equal efficiency. Moreover, if the lightning locations are closer than ∼500 km to the sensor, the detection efficiency also drops. The WWLLN does not obtain good fits to the TOGA when there is significant power in the waveguide modes, such as the TEM mode, which are otherwise strongly attenuated with propagation distance. Thus, the TOGAs calculated from nearby strokes are often less well constrained, and therefore have errors too large to allow their inclusion in the WWLLN database.

At the time of writing, there were 40 WWLLN receivers existing around the world to detect radio wave pulses in real time radiating from lightning strokes within the 6–22 kHz VLF receiver band. However, during the campaign period there were only 29 active receivers as shown in Fig. 2; none of these were located in Canada. Each sensor consists of a 1.5-m whip antenna, a Global Positioning System (GPS) receiver, a VLF receiver, and a processing computer with Internet connection to enable transmission of the data to processing stations. The sensors are located on ferro-concrete buildings around the world because at VLF, they act as conductors and stay at ground potential, hence shielding the antenna from local man-made noise (Dowden et al., 2002). Moreover, in the receiver bandwidth, the vertical electric field from strong lightning dominates over power line noise, therefore, the locations of these receivers do not necessarily have to be in noise-free conditions (Lay et al., 2004).

After collecting the verified TOGA data together at the processing sites, residual minimization methods are used to create high quality data sets of lightning locations. The handling practice for the WWLLN data used in this paper ensures that the time residual for the data collected (indicating the quality of the fit to the data) is less than 30 µs and that the lightning events are detected by at least five WWLLN VLF receiver stations (Rodger et al., 2009). This protocol differs from some previous studies that were performed early in the establishment of the network (Lay et al., 2004; Rodger et al., 2005), as comparisons to regional networks led to improvements in WWLLN data handling practices (Craig Rodger, personal communication, 2009).

## 3 Performance evaluation of the WWLLN

In order to analyze the performance of the WWLLN, lightning stroke data obtained from this network using the most recent Stroke_B algorithm (Rodger et al., 2009) were compared to that from the CLDN. Both data sets were restricted to the grid box 41.7° N to 45.7° N, and 77.4° W to 81.4° W between 1 May 2008 and 31 August 2008, as shown in Fig. 3. This grid box is defined by the location of the Toronto Atmospheric Observatory (TAO), ±2° north-south and ±2° east-west, in southern Ontario. This region was chosen because it experiences frequent lightning activity in the summer, hence the selection of four months in the summer of 2008. Note that the "CLDN" solution set provided by Environment Canada was generated using sensors in both the CLDN and the American equivalent called the National Lightning Detection Network (NLDN); together, these two networks comprise the North American Lightning Detection Network (NALDN). The use of this larger dataset reduces possible location errors due to the region of interest not being surrounded by CLDN sensors, which is the case for the chosen grid box due to its location in southern Canada. The locations of nearby sensors from both networks, along with those from the WWLLN, are also shown in Fig. 3.

During the campaign period, a total of 20 605 WWLLN strokes and 677 406 CLDN strokes were detected within the region of interest. Of the CLDN-detected strokes, 568 152 (~84%) were identified as cloud-to-ground and 109 254 (~16%) were identified as cloud-to-cloud. The mean positive peak current of these CLDN-detected strokes was 14.2 kA and the mean negative peak current was −16.6 kA. The peak current distribution for the strokes is shown in Fig. 4.

To determine the detection efficiency of the WWLLN relative to the CLDN, shared events between the two networks must be identified. Previous comparisons involving WWLLN and other regional lightning detection networks have used several different criteria to define shared strokes. Lay et al. (2004) and Rodger et al. (2005) defined shared events as events that were within 3 ms and 50 km of each other, Jacobson et al. (2006) ensured that events were within 1 ms and 100 km of each other, and Rodger et al. (2006) ensured that they were within 0.5 ms of each other. The latter criterion is the one adopted in this paper for two reasons. Firstly, as noted by Rodger et al. (2006), the WWLLN data are given to microsecond resolution, whereas the CLDN data are given to nanosecond resolution. Because of the high temporal resolution of the data, it is believed that a time criterion alone should be sufficient to characterize shared events. Secondly, following through with this criterion, it is observed that the mean time difference between these shared events (WWLLN − CLDN) was −6.44 µs with a standard deviation of 35 µs, thus producing the time difference histogram shown in Fig. 5. Notice that 0.5 ms is considerably greater than three standard deviations of the distribution (3×35 µs=105 µs). Initially, a spatial criterion of 50 km was also applied along with the time criterion in order to ensure that events considerably separated in space were not considered shared. It was found that this only eliminated 24 shared events and so this spatial criterion was dropped for the results presented here because it did not produce any significant effect.

Using the 0.5 ms time criterion, 19 128 of all the WWLLN-detected strokes were found to be shared with CLDN-detected strokes, thus giving the WWLLN a 2.8% stroke detection efficiency with respect to the CLDN. Conversely, it was found that 18 744 of the cloud-to-ground CLDN strokes and 669 of the cloud-to-cloud CLDN strokes were shared with WWLLN events. The combination of these shared CLDN events sums to 19 413, creating a discrepancy of (19 413–19 128=) 285 strokes. Upon further investigation, it was found that 281 of the shared WWLLN events match two CLDN events, and two of the shared WWLLN events match three CLDN events. The mean positive peak current for the shared events was 59.2 kA and the mean negative peak current was −46.7 kA. The peak current distribution for these shared strokes is shown in Fig. 4 along with that from the CLDN data set alone.

The difference between the mean peak current of the entire CLDN data set and that of the shared data set (14.2 kA and 59.2 kA respectively, for the mean positive currents; −16.6 kA and −46.7 kA respectively, for the mean negative currents) suggests that the WWLLN's current threshold for detection of lightning strokes is much higher than that of the CLDN. This also seems to be the case for the comparisons with the Brazil (Lay et al., 2004), New Zealand (Rodger et al., 2006), and Los Alamos (Jacobson et al., 2006) regional lightning detection networks. Figure 4 confirms this hypothesis, where below the magnitude of 20 kA, the fraction of the entire CLDN data set with peak currents in this range is much greater than that of the shared events. In contrast, outside the ±20 kA range, this relation is reversed. Notice also that there exists a greater fraction of negative lightning strokes than positive as expected (Rakov and Uman, 2003). To further demonstrate the WWLLN current threshold, Fig. 6 shows the detection efficiency of the WWLLN as a function of peak current (assuming that the CLDN detects all lightning events). Notice that below the magnitude of ~20 kA, the detection efficiency is negligible, but for high peak currents, the detection efficiency is between 60% and 85%, reaching ~70% at ±120 kA. The symmetry of the distribution indicates that the WWLLN detects both positive and negative strokes equally well as long as they are above the 20 kA peak current threshold. The oscillations in peak current beyond the dashed vertical lines reflect the lack of statistical data to characterize the behavior in this current range (there are, on average, ~9500 CLDN-detected strokes in each bin, but beyond these dashed vertical lines, each has less than 50).

The same data, when grouped differently, can also be used to observe the effect of the changing ionosphere on the WWLLN detection efficiency. Figure 7 shows the same information as Fig. 6, but divided into two 12-h periods centered on local noon (solid red curve) and local midnight (dashed blue curve). The vertical lines again indicate the current range beyond which there is not enough statistical data to properly characterize the detection efficiency of the WWLLN (less than 25 CLDN strokes in each bin, whereas the average bin contains ∼4700 CLDN-detected strokes). The three points indicating a detection efficiency greater than 100% lie beyond these lines and are the result of the shared data set having one more stroke than the CLDN data set for each of these bins. There is a noticeably higher detection efficiency for local midnight than local noon, however the 20 kA peak current threshold persists for both periods, as does the symmetric nature of the distribution. The changes in detection efficiency are attributed to the difference in the thickness of the ionospheric D-region between night and day. During the night, the D-region disappears, thus providing a clear path for the VLF waves to be reflected by the E-region back towards the ground. During the day, however, the Sun's electromagnetic waves increase the ionization of the ionosphere, producing the D-region, which must be penetrated by the VLF sky waves in order to be reflected by the E-region, thus, losing energy upon each transit of the layer.

The spatial accuracy of the shared events was determined by placing all the shared CLDN events at the origin (0, 0) and plotting the corresponding WWLLN events around this (WWLLN – CLDN). The mean latitudinal offset was −3.14 km with a standard deviation of 5.91 km, and the mean longitudinal offset was 1.62 km with a standard deviation of 6.71 km, as shown in Fig. 8. Note that the CLDN locations are determined from direct line-of-sight ground wave propagation, whereas the WWLLN locations are determined from sky wave propagation, which encounters varying ionospheric conditions along its path. Thus, the small bias observed in the WWLLN results with respect to the CLDN strokes is expected due to the difference in the propagation of the signals detected by the two networks. The mean absolute location accuracy was also evaluated, and is given by the mean of the distances between the shared events. Its value is 7.24 km with a standard deviation of 6.34 km. The earliest study to evaluate the absolute location accuracy of the WWLLN was by Lay et al. (2004), who obtained a value of 20.25±13.5 km. The difference between these results will be discussed in the next section.

Altogether, there were a total of 20 605 events detected by WWLLN, and of these, 19 128 were shared with the CLDN, leaving 1477 unshared WWLLN events. Examining these unshared events, 1466 of them occur within 50 km and 1 h of other CLDN events. Because a typical thunderstorm system ranges from 3 km to >50 km, and the lifetime of an individual cell in such a storm is of the order of one hour (Rakov and Uman, 2003), it can be assumed that these are indeed valid lightning strokes that were missed by the CLDN since its efficiency is not 100%. Therefore, the total number of valid lighting strokes detected in this study is more likely to be 20 594.

The remaining 11 unshared events are considered "outliers". Such events were also observed in past studies (Lay et al., 2004; Rodger et al., 2005; Jacobson et al., 2006). Lay et al. (2004) compared these outlier points to results obtained from a balloon campaign, and the regional network's raw data; Rodger et al. (2005) and Jacobson et al. (2006) both plotted the shared and outlier events and observed that they appeared to be part of the same storm system. Consequently, all of these studies reported that the outlier events were valid lightning strokes that were missed by the regional network due to its efficiency rating. Although the number of outlier events in this study is negligible (0.05% of the WWLLN events detected), this is also the conclusion assumed here. Moreover, if the CLDN region were expanded by 50 km on each side of the WWLLN grid region (the spatial dimension for a typical storm system), it is believed that the number of outlier events will be further reduced because the points close to the boundary of the WWLLN grid region will be treated appropriately when considering the validity of the unshared strokes. We also note that if the total number of events detected by the WWLLN (20 605), rather than the number of events shared with the CLDN (19 128) is used, the detection efficiency of the WWLLN increases slightly to 3.0%.

## 4 Comparison with past studies

There have been several previous studies that have characterized the detection efficiency and location accuracy of WWLLN by comparing it to regional networks around the world (Lay et al., 2004; Rodger et al., 2005, 2006; Jacobson et al., 2006). The findings of these studies, along with those of this paper, are summarized in Table 1.

Lay et al. (2004) used a regional network in Brazil called the Brazil Integrated Network (BIN), and obtained a detection efficiency (0.5%) that was less than a fifth of the value obtained in this study (2.8%). Conversely, the mean absolute magnitude of the peak current they obtained for the shared events (85.7 kA) was much greater than that obtained here (48.4 kA), indicating that the current threshold of the WWLLN has decreased since that study. Furthermore, the error in the mean time difference between the shared events (200 µs) was much larger than the three standard deviations of this study (3×35 µs=105 µs), and as mentioned in Sect. 3, they obtained a mean location accuracy of 20.25±13.5 km whereas the value acquired in this study is 7.24 km with a standard deviation of 6.34 km. These differences are, however, expected because Lay et al. (2004) described their results as a "worse case scenario". That study was performed when the WWLLN had just begun and was functioning with only 11 receivers that were all located more than 7000 km from the region of interest. The WWLLN handling practice also differed, using a 20 µs maximum time residual with each stroke being detected by at least four receiving stations. This WWLLN protocol has since changed, as noted in Sect. 2.2.

Rodger et al. (2005) used the Kattron regional network in Australia for comparison with the WWLLN. The detection efficiency (24.8%) turned out to be much larger than that of any other study, there didn't seem to be a current threshold, the mean time difference was large (490 µs), and more than half of the events detected (56.7%) could not be accounted for and were thus labeled as outlier events. These results may be due to several factors. The data was collected in a single day (13 January 2004), so a malfunctioning of the regional Kattron network over the region of interest is plausible.

There also could have been unusual sferic propagation conditions at that time and location (Craig Rodger, personal communication, 2009). Furthermore, this study was done when the WWLLN was still in its infancy, and so the network may not have been as reliable as its updated versions. In order to resolve this issue, a more in-depth look at the Rodger et al. (2005) results is required, including an analysis of their raw data and the atmospheric conditions present at the time.

The criterion for shared events in this paper matches that of Rodger et al. (2006), who compared the WWLLN to the New Zealand Lightning Detection Network (NZLDN). The detection efficiency (2.7%) obtained by Rodger et al. (2006) is very similar to that obtained in this study (2.8%). However, the number of unshared events recorded was much larger in that study (54.6% of the WWLLN events detected) and was not investigated. This may be due to excellent WWLLN sensor coverage for the region of interest, leading to the WWLLN detecting many strokes that were missed by the NZLDN (Rodger et al., 2006). Unlike the previous study by Rodger et al. (2005), these data were acquired over a period of 15 months (1 October 2003 to 31 December 2004), thus, problems with the regional network must be ruled out. Once again, examining the raw data as well as further analyzing the unshared events would be key to understanding how these issues have arisen.

Finally, Jacobson et al. (2006) obtained similar results to those achieved in this study using five months of data from the Los Alamos Sferic Array (LASA) in Florida. Their study obtained a WWLLN detection efficiency of 0.80% as opposed to the 2.8% acquired here, and together with this study, is the only one that observed WWLLN events shared with multiple local network strokes. Furthermore, a relatively larger number of WWLLN strokes (1.31%) were outlier events compared to 0.05% in this study. It is interesting to note that roughly equal numbers of cloud-to-cloud and cloud-to-ground strokes were detected. This is because LASA is able to detect both types of events equally well, as long as they are of a comparable current magnitude (Jacobson et al., 2006).

## 5 Conclusions

Regional ground-based lightning detection networks exist all over the world, however, they do not extend far beyond national borders. Satellite-based lightning sensors provide valuable data but cannot provide continuous global coverage. The requirement for a truly world-wide lightning detection network is therefore unquestionable and has numerous applications. The WWLLN is such a low-cost, real-time, ground-based network, which has been operational since March 2003, and whose aim is to provide better than 10-km location accuracy globally.

In this paper, both the CLDN and the WWLLN were briefly described, and the performance of the WWLLN was evaluated between May and August 2008 over a region centered on southern Ontario, Canada by using the CLDN as ground truth. It was observed that the WWLLN detected 2.8% of all 677 406 CLDN lightning strokes, increasing to 3.0% if all WWLLN strokes are used. By analyzing the peak currents, the data suggests that the peak current threshold for the WWLLN is ~20 kA, much higher than that of CLDN. The changing ionosphere was observed to affect the WWLLN detection efficiency, resulting in higher detection efficiency at local midnight than at local noon due to the presence and absence of the ionospheric D-region during the day and night, respectively.

The shared events between the two networks were characterized with a $\leq$0.5 ms time criterion, leading to a mean absolute location accuracy of 7.24 km with a standard deviation of 6.34 km. These results were compared to four previous studies performed using other regional lightning detection networks to assess the WWLLN. They were summarized and found to be generally consistent with the results obtained in this paper. In conclusion, the goal for a WWLLN cloud-to-ground location accuracy of less than 10 km has been met. With the addition of more WWLLN receivers, the detection efficiency of the network should continue to improve.

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**Table 1.** Summary of WWLLN comparison studies.

| | Lay et al. (2004) | Rodger et al. (2005) | Rodger et al. (2006) | Jacobson et al. (2006) | Abreu et al. (this work) |
|---|---|---|---|---|---|
| Regional Network Used for Comparison | BIN (Brazil Integrated Network) | Kattron, in Australia | NZLDN (New Zealand Lightning Detection Network) | LASA (Los Alamos Sferic Array), in Florida | CLDN (Canadian Lightning Detection Network), in southern Ontario |
| Data Acquisition Dates | 6, 7, 14, 20, 21 March 2003 | 13 January 2004 | 1 October 2003 – 30 December 2004 | 27 April–10 September 2004 | 1 May–31 August 2008 |
| Region of Interest | 40–55° W, 15–25° S | southeast Australia | 165–180° E, 34–49° S | ≤ 400 km radius circle, centred at 29° N, 82° W | 41.7–45.7° N, 77.4–81.4° W |
| Number of WWLLN Receivers | 11 | 18 | 20 | 19 | 29 |
| WWLLN Handling Practice | •TOA algorithm<br>•time residual ≤20 µs<br>• ≥ 4 receiving stations | •TOGA algorithm<br>•time residual ≤20 µs<br>• ≥ 4 receiving stations | •TOGA algorithm<br>•time residual ≤30 µs<br>• ≥ 5 receiving stations | •TOGA algorithm<br>•time residual ≤30 µs<br>• ≥ 5 receiving stations | •TOGA, Stroke_B algorithm time residual ≤30 µs<br>• ≥ 5 receiving stations |
| Number of Regional Network Strokes[a] | G = 63 893 | Total = 20 182<br>G = 19 313 (95.7%)<br>C = 869 (4.3%) | Total = 224 221<br>G = 204 411 (91.2%)<br>C = 19 810 (8.8%) | Total = 8 923 316<br>G = 4 196 004 (47.0%)<br>C = 4 727 312 (53.0%) | Total = 677 406<br>G = 568 152 (83.9%)<br>C = 109 254 (16.1%) |
| Mean Peak Current of Regional Network[b] | $\|\bar{i}\|$=33.3 kA | $\|\bar{i}\|$=13.8 kA | G: $\|\bar{i}\|$=23.4 kA<br>C: $\|\bar{i}\|$=16.3 kA | [c](–)$\bar{i}$ ~ –18 kA<br>[c](+)$\bar{i}$ ~9 kA | (–)$\bar{i}$=–16.6 kA<br>(+)$\bar{i}$=14.2 kA<br>$\|\bar{i}\|$=16.2 kA |
| Number of Strokes Detected by WWLLN | 671 | 11 609 | 13 459 | 75 884 | 20 605 |

**Table 1.** Continued.

| | Lay et al. (2004) | Rodger et al. (2005) | Rodger et al. (2006) | Jacobson et al. (2006) | Abreu et al. (this work) |
|---|---|---|---|---|---|
| Criteria for Shared Events | $\leq 3$ ms time difference, $\leq 50$ km spatial separation | $\leq 3$ ms time difference, $\leq 50$ km spatial separation | $\leq 0.5$ ms time difference | $\leq 1$ ms time difference, $\leq 100$ km spatial separation | $\leq 0.5$ ms time difference |
| Number of Shared Strokes[d] | Total = 289 (0.5%) | Total = 5006 (24.8%) | Total = 6113 (2.7%)<br>G = 5 923 (2.9%)<br>C = 190 (0.96%) | Total = 71 362 (0.80%)<br>[e]G = 52 728<br>[e]C = 21 437 | Total = 19 128 (2.8%)<br>[f]G = 18 744<br>[f]C = 669 |
| Mean Peak Current for Shared Events[b] | $\lvert\bar{i}\rvert$=85.7 kA | $\lvert\bar{i}\rvert$=14.3 kA | G: $\lvert\bar{i}\rvert$=46.2 kA<br>C: $\lvert\bar{i}\rvert$=41.2 kA | [c](–)$\bar{i} \sim -31$ kA<br>[c](+)$\bar{i} \sim 23$ kA | (–)$\bar{i} = -46.7$ kA<br>(+)$\bar{i} = 59.2$ kA<br>$\lvert\bar{i}\rvert$=48.4 kA |
| Mean Time Difference for Shared Events[g] | $\bar{t} = 60 \pm 200$ µs | $\bar{t} = 490$ µs | $\bar{t} = 32$ µs | NA | $\bar{t} = -6.44$ µs<br>$\sigma = 35$ µs |
| Mean Lat. Long. & Long. | $\bar{x} = +7.3$ km | $\bar{x} = -0.9$ km<br>$\sigma = 2.7$ km | NA | [c]$\bar{x} \sim 2$ km | $\bar{x} = 1.62$ km<br>$\sigma = 6.71$ km |
| Deviation for Lat. Shared Events[g] | $\bar{y} = +3.2$ km | $\bar{y} = +2.8$ km<br>$\sigma = 3.5$ km | NA | [c]$\bar{y} \sim -5$ km | $\bar{y} = -3.14$ km<br>$\sigma = 5.91$ km |
| Number of Unshared Events[h] | 382 (56.9%) | 6603 (56.9%) | 7346 (54.6%) | 4522 (5.96%) | 1477 (7.17%) |
| Criteria For Outlier Points | > 30 km spatial coincidence | If not observed with other campaigns | NA | > 100 km spatial, > 200 ms time coincidence | > 50 km spatial, > 1 h time coincidence |
| Number of Outlier Points[h] | 7 (1.04%) | 6586 (56.7%) | NA | 996 (1.31%) | 11 (0.05%) |

[a] Total strokes as well as number of cloud-to-ground [G] and cloud-to-cloud strokes [C] (% with respect to total).

[b] Positive [+] and negative [–] mean peak current [$\bar{i}$] and when available, mean absolute current [$\lvert\bar{i}\rvert$].

[c] Obtained visually from a graph.

[d] For total, cloud-to-ground [G], and cloud-to-cloud [C], % given with respect to the regional network as ground truth, where possible.

[e] ‘Does not add to the total. In this study, there were (74 165–71 362=) 2803 WWLLN events that had both cloud-to ground [G] and cloud-to-cloud [C] LASA events within ±1 ms.

[f] Does not add to the total. In this study, there were 283 WWLLN events that had multiple CLDN events within ±0.5 ms.

[g] $\sigma$ is a standard deviation, $\bar{t}$, $\bar{x}$, $\bar{y}$ are the mean time, longitude, and latitude differences (WWLLN - CLDN), respectively.

[h] % given with respect to the total WWLLN events detected.

NA = not applicable – used when no data are available.

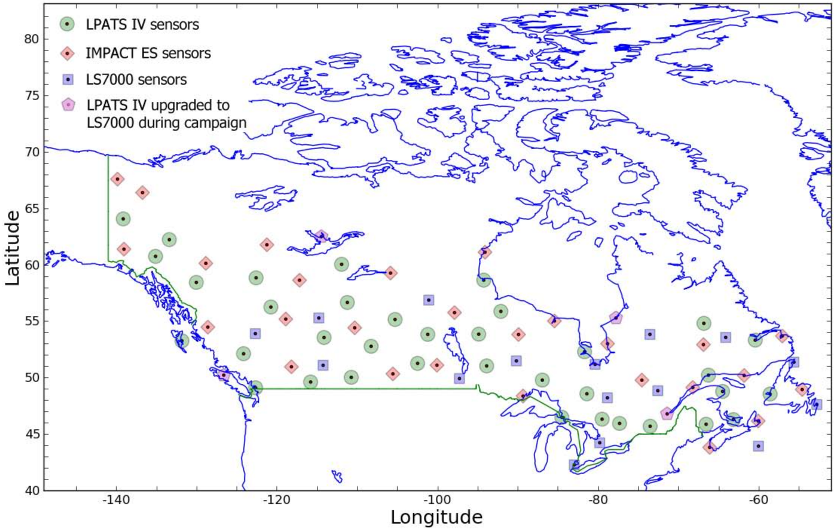

**Fig. 1.** Locations of the CLDN sensors operational during acquisition of the data used in this work.

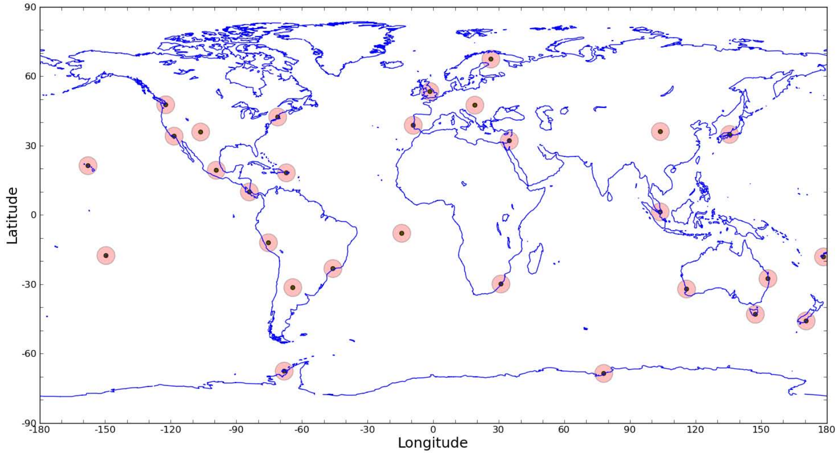

**Fig. 2.** Locations of the WWLLN sensors operational during acquisition of the data used in this work.

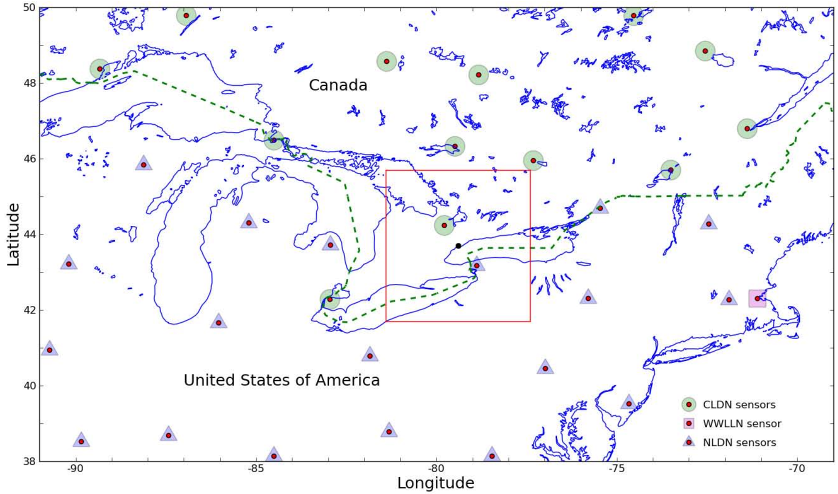

**Fig. 3.** The analysis region used in this study between May and August 2008, represented by the red box. The boundary is the coordinate box 41.7° N to 45.7° N, and 77.4° W to 81.4° W. It is centered around the Toronto Atmospheric Observatory (TAO) located at 43.7° N and 79.4° W, and indicated by the black dot. The locations of nearby CLDN, WWLLN, and NLDN sensors are also indicated.

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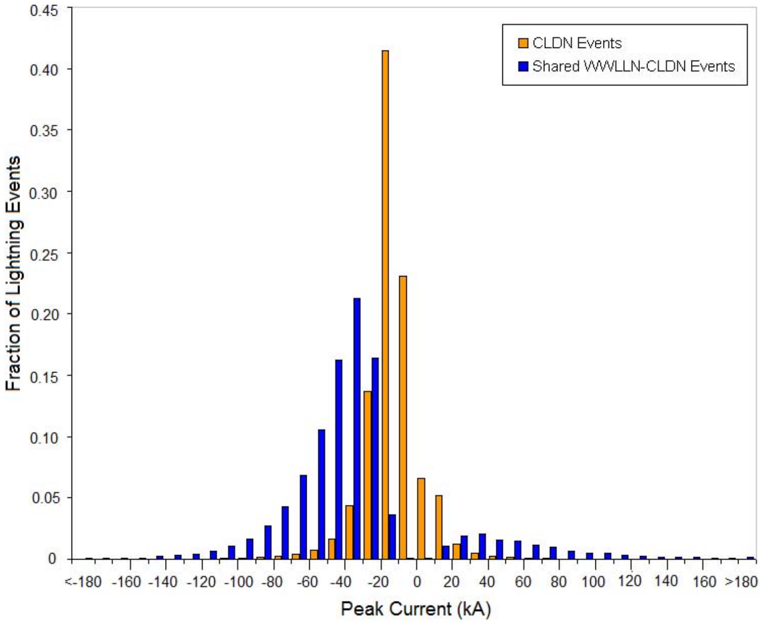

**Fig. 4.** Peak current distribution for the CLDN and the shared WWLLN-CLDN events as determined by the CLDN. Data are grouped into 10 kA bin-sizes, and the outermost bins indicate the number of strokes that are greater than 180 kA in magnitude. The orange bars are all events detected by the CLDN while the blue bars are events shared between the CLDN and the WWLLN.

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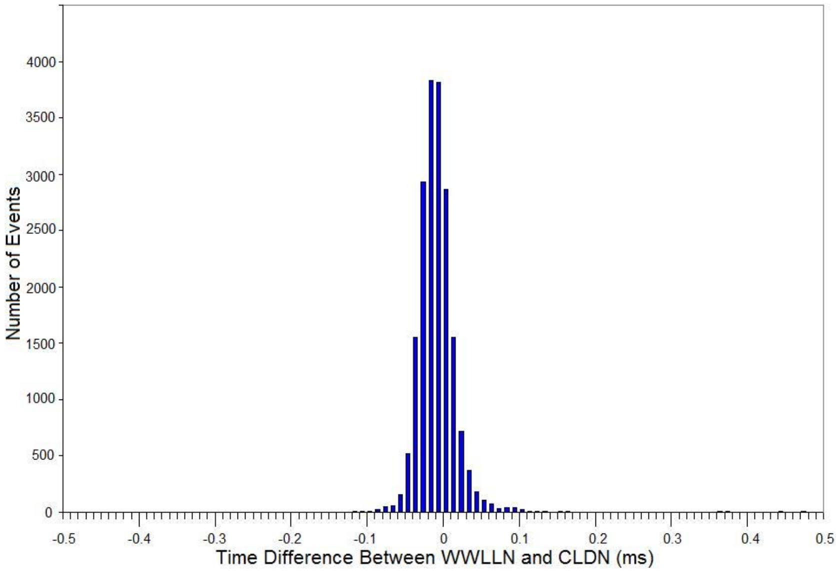

**Fig. 5.** Distribution of the time difference between the WWLLN and CLDN shared events (WWLLN – CLDN) using the 0.5 ms time criterion. Data are grouped into 0.01 ms bin-sizes.

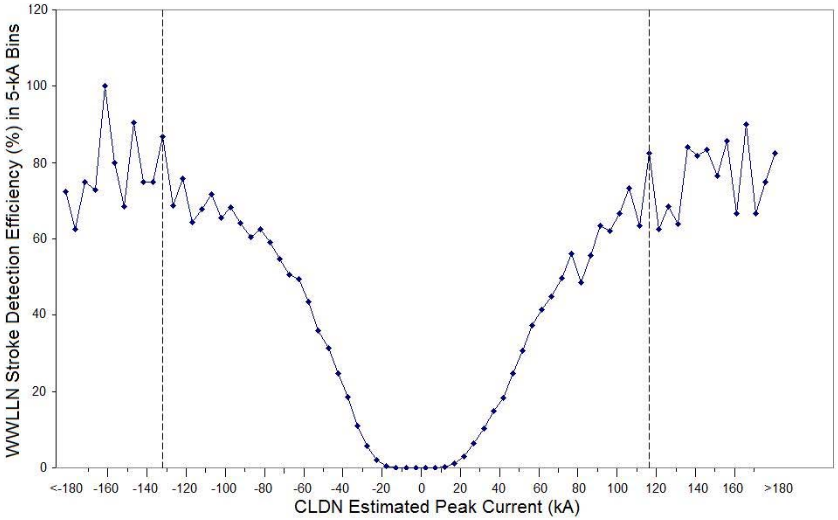

**Fig. 6.** WWLLN stroke detection efficiency distribution taking the CLDN as ground truth. Data are grouped into 5 kA bin-sizes and the outermost bins indicate the detection efficiency for strokes that are greater than 180 kA in magnitude. The vertical dashed lines indicate bins that have fewer than 50 CLDN-detected strokes.

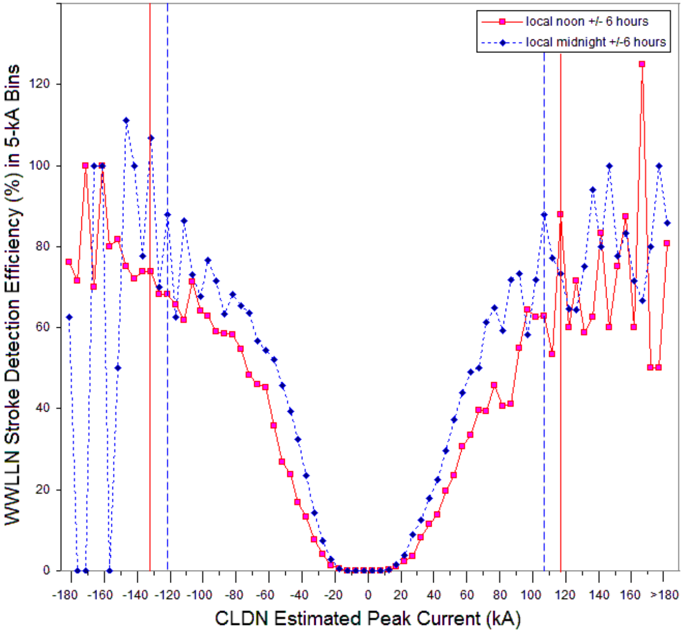

**Fig. 7.** Same as Fig. 6, except the data are now grouped into 12-h periods centered on local noon (solid red curve) and local midnight (dotted blue curve). This demonstrates the effect of ionospheric changes on the detection efficiency of the WWLLN. Bins with fewer than 25 CLDN-detected strokes are indicated by vertical red solid lines and vertical blue dashed lines for strokes detected during local noon and local midnight, respectively.

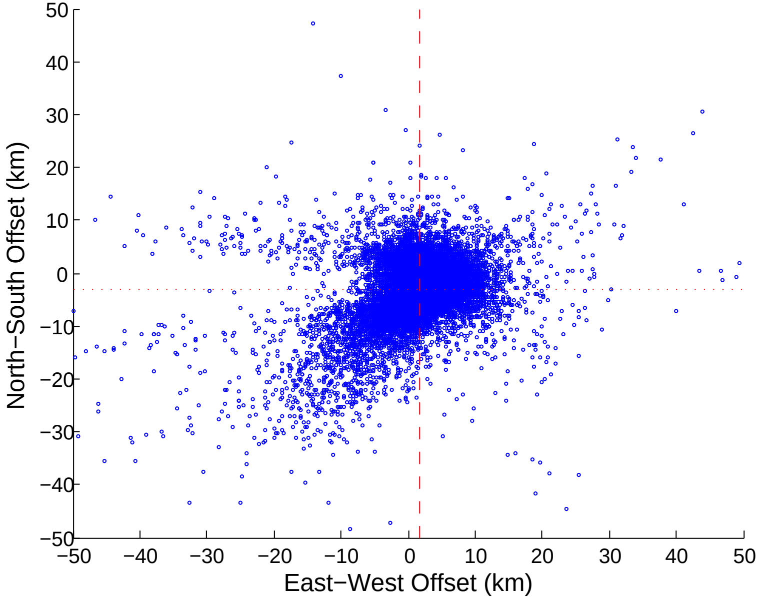

**Fig. 8.** Location offsets between the shared events, taking each CLDN event as the origin and plotting the corresponding WWLLN event relative to it (WWLLN – CLDN). The mean north-south offset is −3.14 km, displayed as the dotted red line, and the mean east-west offset is 1.62 km, displayed as the dashed red line.