An evaluation of the Worldwide Lightning Location Network (WWLLN) using the National Lightning Detection Network (NLDN) as ground truth

Sergio F. Abarca,[1] Kristen L. Corbosiero,[1] and Thomas J. Galarneau Jr.[2]

Received 19 October 2009; revised 24 May 2010; accepted 2 June 2010; published 22 September 2010.

[1] A performance assessment of the Worldwide Lightning Location Network (WWLLN) is presented using the National Lightning Detection Network (NLDN) as ground truth, over unprecedented time and spatial scales. The study spans 3 years, from 5 April 2006 to 31 March 2009, throughout the contiguous United States. The capabilities of the network are shown to improve greatly from the first to the third year of the study, with an overall detection efficiency of cloud-to-ground flashes increasing from 3.88% in 2006−2007 to 10.30% in 2008−2009. The WWLLN cloud-to-ground detection efficiency is found to be strongly dependent on peak current and polarity, attaining values larger than 10% (35%) for currents stronger than ±35 kA (−130 kA) and values less than 2% for currents between 0 and −10 kA. The location accuracy is found to have a northward and westward bias, with average location errors of 4.03 km in the north-south and 4.98 km in the east-west directions, respectively. The WWLLN is shown to have strong limitations in capturing the diurnal cycle, missing both the timing of the maximum and minimum lightning activity (around 1600 and 0900 LT, respectively), and the amplitude of the cycle as well. It is found that in 3 h intervals, the number of flashes in the WWLLN has some proportionality to the number of flashes in the NLDN, suggesting that the WWLLN has strong potential for meteorological applications.

Citation: Abarca, S. F., K. L. Corbosiero, and T. J. Galarneau Jr. (2010), An evaluation of the Worldwide Lightning Location Network (WWLLN) using the National Lightning Detection Network (NLDN) as ground truth, *J. Geophys. Res.*, *115*, D18206, doi:10.1029/2009JD013411.

1. Introduction

[2] The Worldwide Lightning Location Network (WWLLN; operated by the University of Washington) is a developing, experimental lightning detection network increasingly used for applications. Some examples of the wide variety of applications are the quantification of lightning in African easterly waves as a precursor of Atlantic hurricane activity [*Price et al.*, 2007], the search for sprite-induced signatures of middle atmospheric NO_2 [*Arnone et al.*, 2008], and the validation of an independent lightning detection network [*Ortega*, 2007]. The reliability of any of these applications depends on an understanding of the WWLLN's capabilities. Although there have been efforts to evaluate the WWLLN, they are spatiotemporally limited and outdated (the network has practically doubled its number of sensors since the last evaluation). This work presents an evaluation of the WWLLN using the National Lightning Detection Network (NLDN) as ground truth. It spans an unprecedented time period of 3 years and geographical extent of continental scale.

[3] This work is organized as follows: Section 2 describes the two networks and the data sample of the study. A review of previous WWLLN evaluations is presented in section 3. The lightning activity in the data sample and an analysis of the coincident lightning detection efficiency (DE) and location accuracy (LA) is presented in sections 4 and 5. Section 6 presents the diurnal cycle, as captured by the two different networks, and a quantification of storm DE is presented in section 7. Section 8 summarizes and concludes the findings of this study.

2. The WWLLN and the NLDN

[4] The WWLLN (http://www.wwlln.com) locates lightning by using the time of group arrival (TOGA) of the very low frequency (VLF) radiation (3−30 kHz) from a lightning stroke. At each receiving site the dispersed waveform ("sferic") is processed and the TOGA is determined from the progression of phase versus frequency using the whole wave train, lasting a millisecond or more [*Dowden et al.*, 2002]. The stable propagation and low attenuation of VLF waves in the Earth-ionosphere waveguide allows a spacing of the receiver sites of thousands of kilometers, but the ionospheric interaction spectrally distorts the received waveform so that

[1]Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, Los Angeles, California, USA.

[2]Department of Atmospheric and Environmental Sciences, University at Albany/State University of New York, Albany, New York, USA.

0148-0227/10/2009JD013411

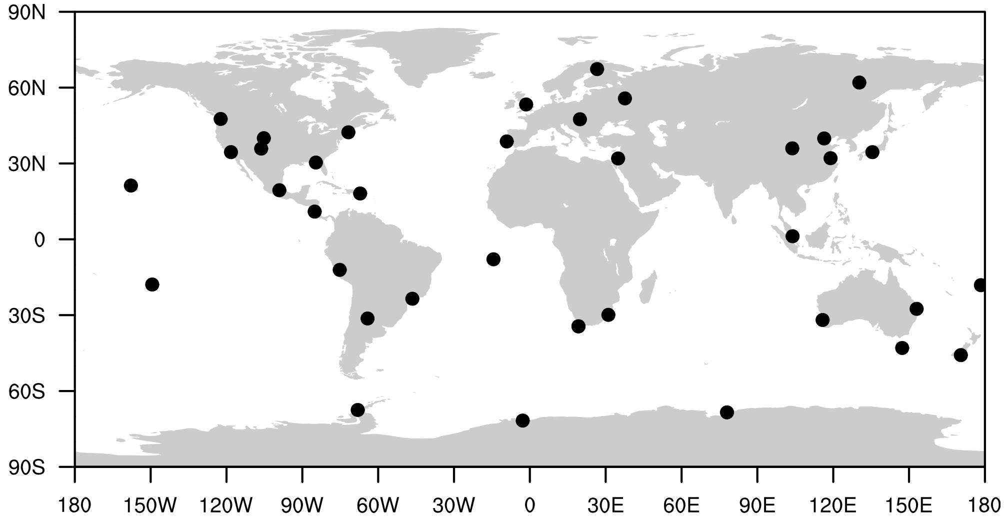

Figure 1. Locations of the 38 WWLLN stations (black circles) operative toward the end of March 2009.

it is not straightforward to infer the vertical current magnitude or polarity.

[5] Figure 1 shows the locations of the 38 stations that formed the WWLLN toward the end of March 2009. Although it is ambiguous to refer to a specific number of receiver sites in operation during a period of time, as some have intermittent service (Robert Holzworth, personal communication, 2009), the network has substantially increased its number of sensors throughout the years, from approximately 28 in 2006 and 30 in 2007, to 32 in 2008 and 38 by the end of March 2009. Unlike most ground-based lightning detection networks, the WWLLN is generally thought to be equally capable of detecting cloud-to-ground (CG) and intracloud (IC) flashes with similar DE as long as they have comparable peak current and channel length [*Lay et al.*, 2004; *Rodger et al.*, 2005, 2006; *Jacobson et al.*, 2006].

[6] The NLDN (operated by the Vaisala Thunderstorm Unit; *Cummins and Murphy* [2009]) provides estimations of a variety of CG lightning characteristics: stroke location, polarity, peak current, and flash multiplicity. The primary objective of the NLDN retrieval is to detect CG flashes; however, some strong IC flashes are included due to limitations of the retrieval and processing of the data. Since April 2006, events with peak currents between 0 and 15 kA and all positive (negative) events with peak-to-zero time ≤15 μs (≤12 μs) are considered cloud discharges and are eliminated from the database [*Fleenor et al.*, 2009].

[7] In the version of the NLDN data used in this study, the flash information is available with 1 s time resolution and with the peak current of the first stroke assigned to the flash. The NLDN detects lightning using both time-of-arrival and direction information through Improved Accuracy through Combined Technology (IMPACT) Enhanced Sensitivity and Performance sensors since a system-wide upgrade that took place during 2002 and 2003 (the previous NLDN configuration, from 1995 to 2002, contained both time-of-arrival Lightning Position and Tracking System sensors and combined time-of-arrival IMPACT sensors and magnetic direction-finding sensors; *Jerauld et al.* [2005]).

[8] *Biagi et al.* [2007] carried out evaluation experiments during 2003 and 2004 and showed a NLDN flash DE of 93% in Arizona and 92% in Texas and Oklahoma. The stroke DE was found to be substantially lower, 68% (77%) in Arizona (Texas and Oklahoma). The primary cause of the NLDN missing strokes was that the peak of the electromagnetic field associated with them was below the NLDN detection threshold. The average DE for negative first strokes, usually stronger than subsequent flashes [*Biagi et al.*, 2007, Table 5], was 92%. The experiments discussed by *Biagi et al.* [2007] also show very high LA, with a median of 0.424 km in Arizona and 0.279 km in Texas and Oklahoma. Although the study of *Biagi et al.* [2007] is based on a limited number of flashes (about 1300), they conducted their experiments in two different geographical regions and in two different time periods with consistent results, suggesting their conclusions are robust.

[9] Studies carried out before (and during) the 2002−2003 NLDN upgrade have also shown a very high DE between 80% and 90% [*Cummins et al.*, 1998; *Idone et al.*, 1998a] and very high LA, on the order of 1 km or less. *Jerauld et al.* [2005] estimated a LA of about 0.6 km using data from rocket-triggered lightning in Florida in the summers of 2001−2003. *Cummins et al.* [1998] obtained a mean LA estimation of 0.5−1.0 km using an idealized model over most of the continental United States for flashes stronger than ±5 kA, and *Idone et al.* [1998b] obtained a LA of 0.435 km using video camera recordings of flashes as ground truth over Albany, New York, during the summers of 1994−1996.

3. Comparisons Between the WWLLN and Other Lightning Location Networks

[10] There are a number of comparisons between the WWLLN and other lightning location technologies. Such comparisons constitute the main evidence for the WWLLN DE and LA. The technologies used to evaluate the WWLLN are other ground-based networks and, to a lesser extent, satellite systems. *Lay et al.* [2007] used the photodiode detector on the Fast On-Orbit Recording of Transient Events satellite [*Suszcynsky et al.*, 2000] to analyze global spatial variations in WWLLN DE. Over North America, they found a relative

Table 1. Summary of WWLLN Comparisons With Other Networks

	Period	Region Lat × Lon	Active Sensors	DE (%)	Mean LA (km)
[*Lay et al.* 2004]	6, 7, 14, 20, and 21 March 2003	Brazil 15° × 15°	11	0.3	20.25 ± 13.5
[*Rodger et al.* 2004]	23, 24 Jan 2003	Australia 8° × 10°	6	1.0	30.0
[*Rodger et al.* 2005]	Feb–Apr 2004	Australia 8° × 10°	18	13.0	3.4
[*Rodger et al.* 2006]	1 Oct 2003 to 31 Dec 2004	New Zealand 15° × 15°	20	5.4	—
[*Jacobson et al.* 2006]	27 Apr to 30 Sept 2004	Florida Circle with radius of 400 km	19	<1.0	15–20

DE of 0.9%, much lower than the WWLLN DEs reported in studies comparing the WWLLN to other ground-based networks (see below) because the majority of the satellite-based detections are IC flashes, whereas the WWLLN mainly detects CG flashes.

[11] Table 1 summarizes the published comparisons of the WWLLN against other ground-based networks. The table shows that the DE of the WWLLN is generally very low, a few percent of the total lightning. This limitation of the WWLLN offers the challenge of how to use its data meaningfully. This challenge can only be met by a thorough understanding of the characteristics of the data. Table 1 also shows large discrepancies in both the DE and LA estimations. DE was evaluated to be 0.3% [*Lay et al.*, 2004] in March 2003 over a region of Brazil, whereas in the latest evaluation, carried out from April to September 2004 over a region of Florida, DE was evaluated to be close to 4% for peak currents larger than −50 kA [*Jacobson et al.*, 2006]. The highest WWLLN DE reported is 13% over a region in Australia [*Rodger et al.*, 2005].

[12] There are a number of reasons that may account for the discrepancies in the results summarized in Table 1. Some of the reasons pertain to the configuration of the WWLLN itself. For example, the network has substantially increased its number of sensors throughout the years. The number of sensors went from 11 during its first evaluation in 2003 to 20 during the latest evaluation in 2004. The network has also incorporated increasingly more sophisticated signal processing algorithms [*Rodger et al.*, 2004, 2005, 2009]. Additionally, the WWLLN is expected to have different capabilities in different parts of the world due to the variations in network density (see Figure 1).

[13] Another reason for the discrepancies between the previous WWLLN evaluations has to do with the diversity of networks used as ground truth to evaluate the WWLLN. These networks have their own limited DE, usually estimated to be around 80%, e.g., the Brazilian Integrated Network [*Lay et al.*, 2004], Kattron [*Brundell et al.*, 2002], and the New Zealand Lightning Detection Network [*Rodger et al.*, 2006]. Most of these networks focus their detection on CG flashes, but one of them, the Los Alamos Sferic Array [*Jacobson et al.*, 2006], has comparable DE for CG and IC flashes, as long as they have comparable peak current and channel length. It is important to note that to estimate the overall DE from the networks that measure only CG flashes, rough estimates of the corresponding number of IC flashes are made. To do this, *Rodger et al.* [2004, 2005] assumed that there are 3.5 times more IC flashes than CG flashes following *Mackerras et al.* [1998].

[14] The described WWLLN evaluations have substantial spatiotemporal limitations as well. Table 1 shows the size of the evaluation area. The largest areas of evaluation have been ~15° × 15° by *Lay et al.* [2004] and *Rodger et al.* [2006]. This local scale of the evaluation area lays in stark contrast with the global scale of the WWLLN. Global-scale evaluation can only be accomplished by satellite comparison, but these technologies have their own limitations and are not suitable for a WWLLN DE and LA assessment as noted in the work of *Lay et al.* [2007]. Besides the spatial limitation, the time interval of the evaluations has also been limited, with only one evaluation spanning a period of time longer than a year and none reaching 2 years. This limitation has precluded a systematic assessment of the time evolution of the WWLLN. The period of evaluation has ranged from 15 months [*Rodger et al.*, 2006] to a couple of days [*Rodger et al.*, 2004]. The latter reference and *Lay et al.* [2004] used less than 700 WWLLN flashes to draw their conclusions. With such a small sample, part of the discrepancy in the estimation of the WWLLN capabilities presented in Table 1 may be due to the limited sample size.

[15] Finally, besides the spatiotemporal limitations of the WWLLN evaluations, they are also outdated. Since the last evaluation, when the number of sensors was 20 (December 2004), the network has grown substantially to approximately 38 sensors toward the end of March 2009 and to over 40 at the time of writing. The WWLLN is thus overdue for a thorough evaluation of its DE and LA capabilities.

4. Lightning Activity in the Sample

[16] The WWLLN evaluation presented in this work spans 5 April 2006 to 31 March 2009. Within this time period, the reported flashes in each network from 25°N to 45°N and from 125°W to 75°W are considered. Following the advice of the WWLLN developers, only those lightning locations that triggered at least five sensors and that had residuals ≤ 30 μs are regarded as good locations and are included in this analysis. The processing algorithm to obtain the data of this analysis is the latest released, and it has been estimated that the algorithm generates 63% more lightning locations than the previous algorithms [*Rodger et al.*, 2009]. Regarding the NLDN, the application of the criteria to filter out IC flashes (see section 2) leaves no positive flashes with peak current $\leq$15 kA. The number of WWLLN and NLDN flashes per year included in this study is presented in Table 2.

[17] Figure 2 shows flash density for 5 April 2006 to 31 March 2007 and 1 April 2008 to 31 March 2009 computed in units of the number of flashes per square kilometer per year, as captured by each network. Notice that the contour interval limits for the NLDN are an order of magnitude larger than those for the WWLLN. It can be seen that the WWLLN roughly captures the geographic variability of flash density exhibited by the NLDN. The maximum in flash density over the central United States is clearly reproduced in 2008–2009 and is also present to a lesser extent in 2006–2007 when the number of flashes reported by the WWLLN

Table 2. Number of Flashes Reported by the WWLLN and the NLDN, by Year, Between 25°N–45°N and 125°W–75°[a]

Year	2006–2007	2007–2008	2008–2009
All WWLLN flashes	2,732,366	3,228,444	6,154,394
All (CG) NLDN flashes	29,614,920	27,567,606	24,839,997
Coincidences	1,147,815	1,346,692	2,558,809
CG DE (%)	3.88	4.89	10.30
IC DE (%)	1.78	2.28	4.82
CG + IC DE (%)	2.31	2.93	6.19

[a]All coincident flashes and the estimated DE are included. See the text for an explanation on how the estimations are performed.

was remarkably smaller (see Table 2). The maximum in flash density over western Mexico associated with the North American Monsoon and the flash density signature of the region's topographical features are well captured by the WWLLN, as is the relative minimum on the western side of the Appalachian Mountains. The Gulf Stream flash density maximum is also very well captured by the WWLLN, and since the DE of the NLDN decreases with the distance from the shore, this feature is likely to be better represented by the WWLLN.

[18] Interestingly, in the region of Florida, the contrast in flash density between continental and oceanic surfaces seen by the NLDN is apparently not captured by the WWLLN. This discrepancy may be a manifestation of the bias that the WWLLN has toward stronger flashes (see section 5.1). According to the NLDN peak current estimates over a region of the Florida peninsula (from 26.0°N to 27.5°N and 82°W to 80°W), the average peak current (independent of polarity) is 18.39 kA, whereas over an oceanic region just east of Florida (for the same parallels but between 80°W and 78°W), it is 28.24 kA. Stronger flashes over the ocean than over the continental region of the southeastern United States have been documented by many authors [i.e., *Lyons et al.*, 1998; *Orville and Huffines*, 2001; *Steiger and Orville*, 2002, 2003], and *Lyons et al.* [1998] proposed that the high conductivity of the underlying saltwater may be the reason for the large number of intense negative CG flashes striking the ocean. However, it remains unclear whether the observed increase is the result of a change in the relationship between flash signal strength and peak current over salt water or an actual peak current enhancement [*Pessi et al.*, 2009] or even if the higher conductivity of the ocean water is the only causative factor [*Lyons et al.*, 1998; *Orville and Huffines*, 2001; *Steiger and Orville*, 2002, 2003]. Another factor possibly contributing to the WWLLN not showing the continent versus ocean contrast seen in the NLDN could be differences in the IC-CG ratio, termed *Z*, between these two surfaces. However, a lack of documented *Z* differences between land and ocean precludes further analysis at this time.

5. Coincident Lightning

[19] To make comparisons between CG lightning discharges located by the WWLLN and the NLDN, the coincident lightning has to be identified. Previous studies have attempted to identify coincident lightning between the WWLLN and other sources of data [*Rodger et al.*, 2004, 2005, 2006; *Jacobson et al.*, 2006; *Lay et al.*, 2007]. In all of these studies, the criteria to determine which events are coincident events have been to establish a time/space window within which an event reported by both networks is regarded as the same event. The choice of the size of the time/space window is arbitrary and was chosen depending on the data characteristics. The time window has ranged

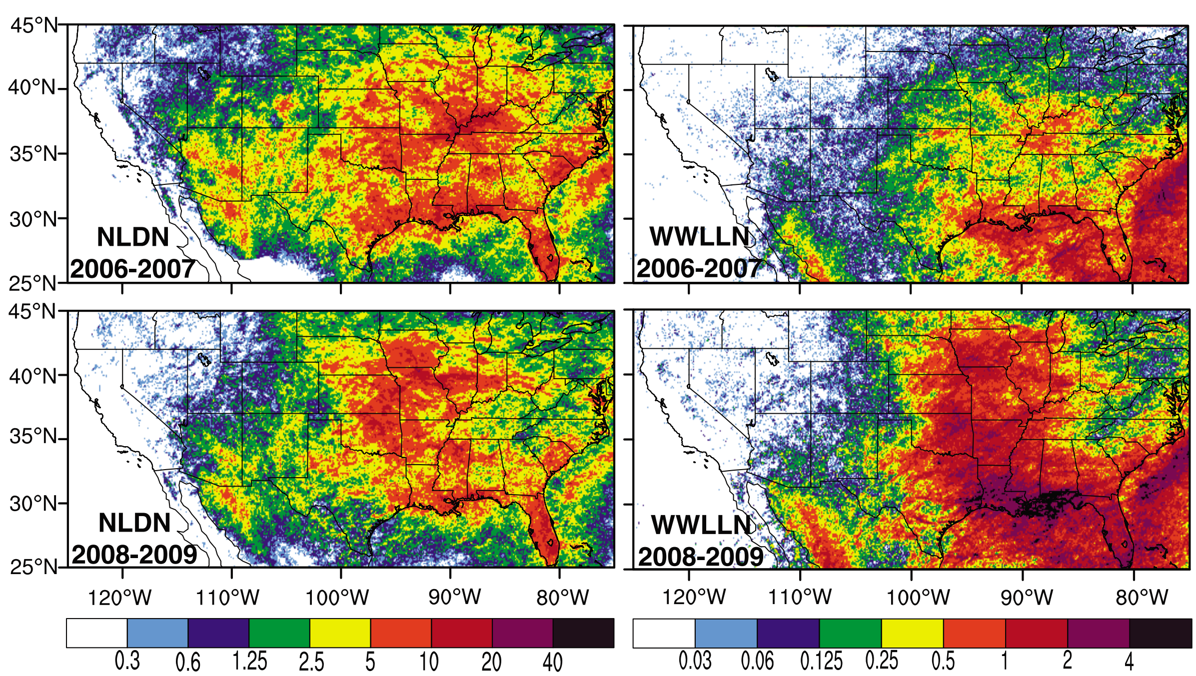

Figure 2. Flash density in number of flashes per square kilometer per year, for (top) 2006–2007 and (bottom) 2008–2009 as seen by (left) the NLDN and (right) the WWLLN.

from ±25 [*Rodger et al.*, 2005] to ±0.5 ms [*Rodger et al.*, 2006]. With this narrow range, the time window has been the primary parameter of identification for coincident events. The typical spatial window in previous studies has ranged from 50 to 100 km. Alternatively, *Rodger et al.* [2006] verified the WWLLN without any spatial criterion. They argued that the small time window (±0.5 ms) by itself would suffice to identify coincident lightning.

[20] In the current study, the space window will serve as the primary parameter of identification of coincident events since the available data from the NLDN has the coarse time resolution of 1 s. The WWLLN LA has been estimated to be between 15 and 20 km [*Jacobson et al.*, 2006] and even more precise by other studies [*Rodger et al.*, 2005]. *Rodger et al.* [2004] estimated the LA to be 30 km, but that estimation was done with only 2 days of data during January 2003. On the basis of these results, the space window we use is a circle of 20 km radius. To assess the effects of this choice on the LA results, 15 and 30 km are also tested.

[21] Regarding the time window, the WWLLN has a resolution of microseconds, and for comparison with the NLDN, each WWLLN flash is assigned the closest whole second to the time of its occurrence. Once WWLLN discharges have been assigned the closest second of their occurrence, events reported by the two networks within the same second and up to 20 km from each other are considered coincident lightning. In the rest of the study, we assume our choice of space/time window sufficient to identify coincident lightning.

[22] With the NLDN time resolution constraint (1 s), it is not possible to determine with absolute certainty whether the identified coincident flashes are also coincident strokes. However, to determine the peak current of coincident flashes (sections 5.1 and 6), it is assumed that coincident flashes are also coincident strokes. Since the WWLLN DE is biased toward stronger discharges and the NLDN assigns the peak current of the first stroke to the flash, which is often the strongest [*Biagi et al.*, 2007; their Table 5], more often than not, the identified coincident flashes are also expected to be coincident strokes. However, in those cases where one of the subsequent strokes had the largest peak current, our methodology is likely to underestimate the peak current of the discharge located by the WWLLN.

5.1. Detection Efficiency

[23] Table 2 shows the yearly total number of flashes as reported by each network, the coincident events and estimations of the DE of CG, IC, and all (CG + IC) flashes. The DE of CG flashes is calculated directly as the percentage of NLDN (CG) flashes that had a WWLLN coincident event. In this estimation, as in previous publications [e.g., *Jacobson et al.*, 2006], it is assumed that the NLDN is the ground truth (with a DE of 100%). This assumption may result in an overestimation of the WWLLN DE proportional to the departure of the NLDN DE from 100%, or an underestimation of the WWLLN DE proportional to the number of flashes missed by the NLDN and captured by the WWLLN. Therefore, the results in this section should be considered carefully.

[24] To calculate the DE of IC and all (CG + IC) flashes, an estimation of the number of IC flashes must be made. This estimation is traditionally obtained from the measured number of CG flashes, by assuming a value for Z. Until recently however, Z estimates have been relatively rare and have a wide range of values: *Mackerras et al.* [1998] estimated a global value of Z of 3.5, *De Souza et al.* [2008] found Z ranging from 2 to 12 in Southeastern Brazil, and *Rivas and de Pablo* [2007] obtained an average Z of 3.48 with large variability in their domain of study over the Iberian Peninsula. A recent estimate over the continental United States, using the NLDN and the Optical Transient Detector from 1995 to 1999, yielded a somewhat smaller value of 2.94 ± 1.28 with large spatial variability [*Boccippio et al.*, 2001, Figure 2]. Considering these results, $Z = 3$ was assumed in this work. A variation of 1% in the value of Z would result in a variation of about 1% in the IC DE estimation and about 0.74% in the estimation of the DE of all (CG + IC) flashes. It is also assumed that all of the noncoincident WWLLN events are IC flashes, as the analysis in section 7 suggests and as previous studies have argued [*Rodger et al.*, 2005]. The overall (CG + IC) DE was estimated adding the NLDN (CG) flashes to the estimate of IC flashes and taking the resulting number as ground truth.

[25] The WWLLN DE has been steadily increasing with time in the region of study. Table 2 shows that, for every flash category, the DE increased by a factor of approximately 2.5 from 2006–2007 to 2008–2009. The table also shows that the number of flashes increased steadily from around 2.7 million in 2006–2007 to around 3.2 million in 2007–2008 and to more than 6 million in 2008–2009. The increase over the years considered, with the largest increase in 2008–2009, has occurred with an increase in the number of sensors in the network (see section 2) and is consistent with *Rodger et al.* [2009] who found an increase in the global detection from 18.1 million flashes in 2005 to 24.4 and 28.1 million in 2006 and 2007, respectively. Table 2 shows that the IC DE is consistently about 45% of the CG DE. This is somewhat higher than the previously reported 38% in the study by *Rodger et al.* [2005]. This discrepancy may be a direct result of the choice of Z value, as when the results are computed with $Z = 3.5$, the IC DE becomes 40% of the CG DE.

[26] A number of coincidences (484,730; 0.59% of the total NLDN flashes and 9.59% of the coincidences) occurred between one WWLLN flash and two or more NLDN flashes (up to seven, with only two cases of six coincidences and one case with seven coincidences). Coincidences with two NLDN flashes were the majority of these multiple coincidences (452,287; 0.55% of the NLDN flashes and 8.95% of the coincidences). This multiplicity of coincidences is a consequence of the coarse time window used in this study given by the time resolution of the NLDN data available. It is not possible to distinguish which of the NLDN flashes in the multiple coincidence cases was actually the one located by the WWLLN, and the rest of the study focuses only on those flashes with one coincidence. This may be introducing a bias in our results, since with this, we will be removing those events with multiple flashes within the same second and in the same 20 km radius, the implications of which are discussed below.

[27] Figure 3a shows the distributions of NLDN estimated peak current for all the NLDN-detected flashes (solid line) and the subset that had a coincidence with the WWLLN (dashed line) in bins of 2 kA. It shows that the sample is heavily weighted toward negative flashes, consistent with

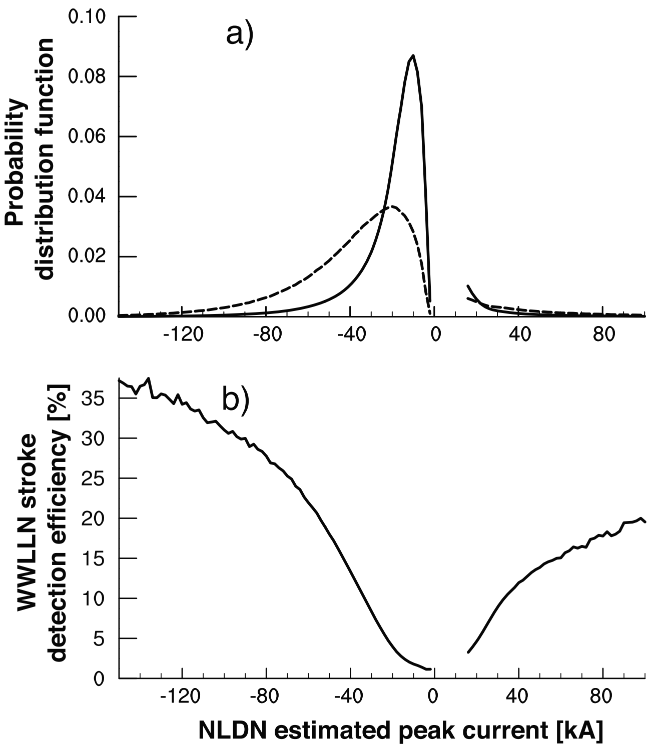

Figure 3. (a) Distribution of NLDN-estimated peak current for all flashes (solid line) and those flashes with WWLLN coincidences (dashed line) and (b) distribution of WWLLN flash detection efficiency. Bin size is 2 kA.

the climatology of the continental United States [*Carey et al.*, 2003; *Orville and Huffines*, 2001]. Since the NLDN peak current is obtained from the first NLDN-detected stroke, cases of coincident flashes in which the strongest NLDN stroke is actually a subsequent one are likely to be assigned a lower peak current than the one that triggered the WWLLN receivers. These cases would bias the coincident flash peak current toward smaller values, but since the first NLDN-detected stroke tends to be stronger than subsequent strokes [*Biagi et al.*, 2007], these cases are not expected to dominate the distribution in Figure 3. Indeed, Figure 3 shows that the NLDN subset with WWLLN coincidences is shifted to higher current amplitudes with respect to the background distribution, consistent with previous studies [*Lay et al.*, 2004; *Rodger et al.*, 2004, 2005; *Jacobson et al.*, 2006] and confirming the WWLLN DE bias toward stronger peak current events and suggesting that the assumption of coincident flashes as coincident strokes is adequate.

[28] Using the subset of coincident events, Figure 3b shows the WWLLN DE estimation as a function of peak current. This estimation is calculated for each 2 kA bin, dividing the number of coincident flashes by the number of all flashes detected by the NLDN, as in the work of *Jacobson et al.* [2006]. The large study sample resulted in a substantial amount of data available in every bin of the range considered, with the smallest number of coincident flashes in a single bin corresponding to the range −151 to −149 kA with 1898 events. Despite the fact that the figure contains an underestimation of the actual WWLLN DE in the sample (recall that 9.59% of the coincidences, the cases of multiple coincidences, are omitted from this analysis), it shows higher WWLLN DE than previously reported, reaching more than 35% for the strongest negative currents. The DE decreases with decreasing peak amplitude down to a minimum of 1.14% in the −3 to −5 kA bin. Peak currents stronger than −35 kA (−55 kA) have a DE higher than 10% (20%). As is the case for the negative flashes, the DE of positive flashes grows with peak amplitude. The lowest DE in the positive peak current range studied is 3.26% in the 15−17 kA bin. From that bin, the DE grows to a maximum of 20% for the strongest flashes considered. Figure 3b shows a higher DE than the one reported for CG events by *Jacobson et al.* [2006]. The difference may be the result of the improvement in network density since the time of the *Jacobson et al.* [2006] study (summer 2004) and the use in this study of the new signal-processing algorithm described by *Rodger et al.* [2009].

5.2. Location Accuracy

[29] Figure 4 shows the distributions of the north-south and east-west distance differences between the NLDN and WWLLN locations of coincident flashes using 15, 20, and 30 km as the spatial window. It shows WWLLN northward and westward biases that are, on average, 4.03 and 4.98 km, respectively, for the 20 km window. Figure 4 also shows that changing the spatial window criteria does not result in dramatic changes in the LA distributions as the largest changes between different criteria are on the order of .5 km. Since we are unable to determine which of the NLDN flashes in the multiple coincident cases actually corresponds to the WWLLN flash, we cannot quantify how the omission of the multiple coincident events is affecting the LA estimation of this sample.

[30] Although spatial location biases depend on a number of factors including lightning climatology and Earth-ionosphere waveguide conditions and therefore cannot be compared between two different regions of the world and

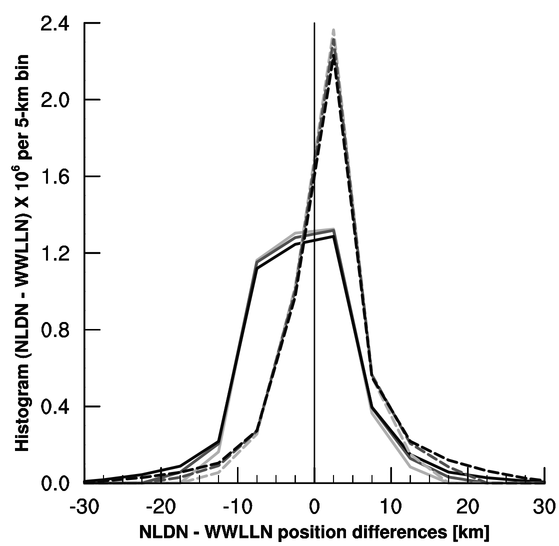

Figure 4. Distributions of NLDN-WWLLN zonal (solid) and meridional (dashed) location differences for 15 (light gray), 20 (dark gray), and 30 km (black) spatial window. Bin size is 5 km.

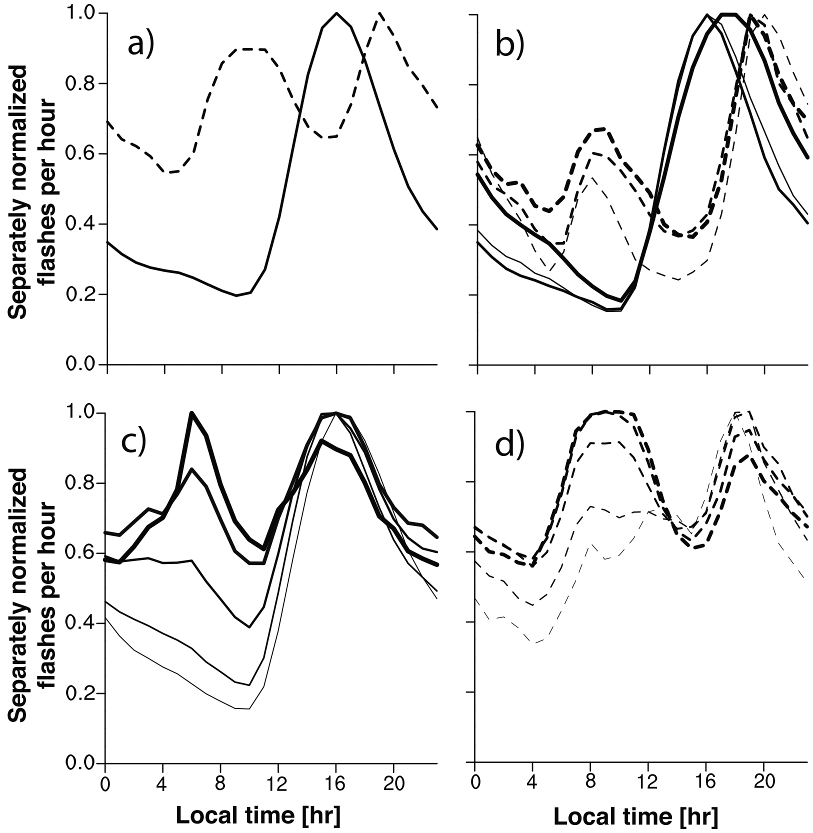

Figure 5. Diurnal cycle as captured by the NLDN (solid lines) and the WWLLN (dashed lines), for (a) the domain of the study (25°N–45°N and 125°W–75°W) and (b) for a domain including only continent (32°N–45°N and 115°W–82°W). (b) The thin lines correspond to the year 2006–2007, the medium lines correspond to 2007–2008, and the thick lines correspond to 2008–2009. (c) Contains the diurnal cycle as captured by the NLDN in bins of 30 kA, for negative flashes in the continent-only domain. The thinnest line corresponds to the weakest flashes (up to −30 kA), and the thickest line corresponds to the strongest flashes considered (−120 to −150 kA). (d) Same as Figure 5c but for the WWLLN. Each (1 h) time bin and network is normalized independently to facilitate comparison.

two different time periods, here we review the previous results published in the literature regarding LA to contextualize the presented results. In previous studies, there is no consensus on the direction of the bias. In the zonal direction, an eastward bias was found, with an average of 7.3 km by *Lay et al.* [2004] and with a median of ~8 km by *Rodger et al.* [2004]. However, *Rodger et al.* [2005] found a westward bias with a median of ~0.9 km, in agreement with the results of *Jacobson et al.* [2006, Figure 3]. In the meridional direction, a northward bias was found, with an average of 3.2 km by *Lay et al.* [2004] and with a median of ~2.8 km by *Rodger et al.* [2005], in agreement with the results of *Jacobson et al.* [2006, Figure 3]. *Rodger et al.* [2004], however, found a southward bias with a median of ~1 km.

[31] Despite the lack of consensus in previous studies on the direction of the bias, the results of this work are roughly consistent with them in that there is a wider distribution of location errors in the zonal direction (see Figure 4). The results of this work also agree with the rest of the studies discussed in this section in that the WWLLN bias is small enough to ensure that WWLLN locations are indicative of the convective system in which they are taking place but perhaps not of the individual convective cell.

6. Diurnal Cycle

[32] Figure 5a shows the diurnal cycle of all the discharges in the data sample, as captured by the NLDN (solid) and the WWLLN (dashed). For the diurnal cycle calculations, the lightning flashes were assigned their local mean solar time (LT), a function of longitude, such that the Sun crosses the local meridian at 1200 LT. In Figure 5a, the data are separately normalized to facilitate comparison of the time variation in flash density reported by each network. The NLDN exhibits a diurnal variation with a maximum at 1600 LT and a minimum at 0900 LT. The amount of flashes at the maximum is 5 times larger than at the minimum. These results are consistent with the 5 year, NLDN-based study by *Zajac and Rutledge* [2001], which shows a similar structure of the diurnal variation with flash rates peaking between 1400 and 1600 LT.

[33] The WWLLN exhibits a very different diurnal structure. It has two maxima, the largest at 1900 LT and a

smaller and broader maximum between 0800 and 1100 LT. The two associated minima occur at 0400 and 1700 LT. The weaker minimum occurs at 1700 LT, close to the timing of the only maximum in nature evidenced by the NLDN. A number of factors are related to this diurnal cycle structure. The effects of including ocean in the domain of study, the changing WWLLN receiver distribution, changes in ionospheric composition throughout the day, and the variation of the diurnal cycle with flash strength are explored as possible causes below.

[34] *Lay et al.* [2007, Figure 5a] studied the diurnal cycle over North America separating land and oceanic domains. In their continental case, a weak, secondary maximum can be distinguished at 0700 LT, although dramatically weaker than the main maximum at 1900 LT. The oceanic diurnal cycle has much smaller amplitude than its continental counterpart and contains two broad and subtle maxima: the stronger peaking around 0000 LT and the weaker peaking around 1000 LT. This is consistent with many other studies that show an early morning maximum in oceanic lightning and rainfall [e.g., *Lucas and Orville*, 1996; *Petersen et al.*, 1996; *Nesbitt and Zipser*, 2003; *Zipser et al.*, 2006].

[35] To assess the extent to which the inclusion of ocean in our domain could be influencing the diurnal cycle structure captured by the WWLLN, a second, continent-only domain, extending from 32°N to 45°N and from 82°W to 115°W, is considered. Figure 5b shows the diurnal cycle as captured by the NLDN (solid) and the WWLLN (dashed) in the continent-only domain, for 2006–2007 (thin lines), 2007–2008 (medium lines), and 2008–2009 (thick lines). The flashes were separated by year to test whether the increasing number of WWLLN sensors may factor into the discrepancies between the networks. For the NLDN, Figure 5b shows that the diurnal cycle maintains its general structure and timing, with slightly more accentuated amplitude as expected from the exclusion of the oceanic portion of the domain. Figure 5b also shows some interannual variability with a larger proportion of flashes overnight and into the morning hours in the year 2008–2009. This larger amount of flashes could be the result of higher flash density during 2008–2009 over Nebraska, Kansas, and Oklahoma, as well as the western parts of Iowa, Missouri, and Arkansas (Figure 2), due to eastward propagating mesoscale convective systems that contribute strongly to the diurnal cycle of precipitation in this longitude band from the evening to midmorning hours [*Carbone et al.*, 2002; *Carbone and Tuttle*, 2008].

[36] The WWLLN diurnal cycle in the continent-only domain still presents two daily maxima even when considering only continental flashes but with a much weaker morning peak (Figure 5b). This decrease in the morning peak shows progressive changes with time, and although some of these changes could be related to interannual variability, it is likely that they are mostly due to the improvements in network density (section 2). As time advances and network density improves, the WWLLN diurnal cycle shows a progressive diminishment of the relative minima in lightning activity and the morning maximum gets smaller relative to the late afternoon maximum. In addition, the WWLLN late afternoon maximum is shifting to earlier times, in closer agreement with the NLDN.

[37] Besides the possible influence of including ocean in the domain of study and improvements in network density, a lower ability of the WWLLN to locate lightning around local noon is expected because of higher electromagnetic signal attenuation under the daytime ionosphere associated with ionization density changes in the Earth-ionosphere waveguide [*Watt*, 1967]. *Rodger et al.* [2006] showed that the detection range for a particular receiver is larger around local midnight than around local noon (see their Figure 11). Changes in DE associated with day versus night environments have also been investigated using the Long-range Lightning Detection Network by *Pessi et al.* [2009] who found a flash DE in the north Central Pacific in the range of 17%–23% (40%–61%) for daytime (nighttime) conditions.

[38] Different diurnal cycles of different flash strengths may also be playing a role in the observed WWLLN diurnal cycle. Using NLDN data for 14 summer months (1991–1995), *Lyons et al.* [1998] documented a double maxima of negative CG flashes stronger than −75 kA over the continental United States, with the stronger maximum before midnight and the weaker in the early afternoon. Figures 5c and 5d show the diurnal cycle of NLDN and WWLLN negative coincident flashes separated by peak current. In Figures 5c and 5d, each line corresponds to a bin of 30 kA, with the thickness of the line proportional to the strength of the flashes, i.e., the thinnest line includes the weakest flashes (up to −30 kA) and the thickest includes the strongest flashes considered (−120 to −150 kA). Each line has been independently normalized to facilitate comparison. In the bin including the weakest flashes there might be a larger (with respect to the rest of the bins) incidence of cases where coincident flashes are not coincident strokes. In these events, a weaker peak current (of the first stroke that the NLDN uses as the flash peak current) is assigned to the coincident flash when it is possible that the discharge located by the WWLLN might be one of the subsequent (stronger) strokes. However, it is unlikely that this relative higher incidence of the underestimation of flash peak current would dominate the diurnal cycle for the bin with the weakest flashes since the bin has a large amount of events (see Figure 3a), and in general, the first stroke tends to be the strongest [*Biagi et al.*, 2007].

[39] Figure 5c shows that the NLDN itself shows a secondary maximum for the stronger flashes that increases with flash peak current magnitude. The double maximum structure found is in agreement with the study by *Lyons et al.* [1998], but the timing is different and the relative strength of the maxima is reversed for the strongest flashes. Despite the NLDN exhibiting double maxima for the stronger flashes, a comparison between Figures 5c and 5d suggests that the WWLLN double maximum is not a result of the DE bias that this network has toward stronger flashes. Thus, the strong peak current bias in the WWLLN is not likely to explain the differences between the NLDN and WWLLN diurnal cycles, and the authors are currently investigating the topic in further detail.

[40] Although the effects of including ocean in the original domain of study, the changing WWLLN receiver density, as well as the effects of changes in ionosphere composition throughout the day and variation of the diurnal cycle with flash strength all have an impact on the observed

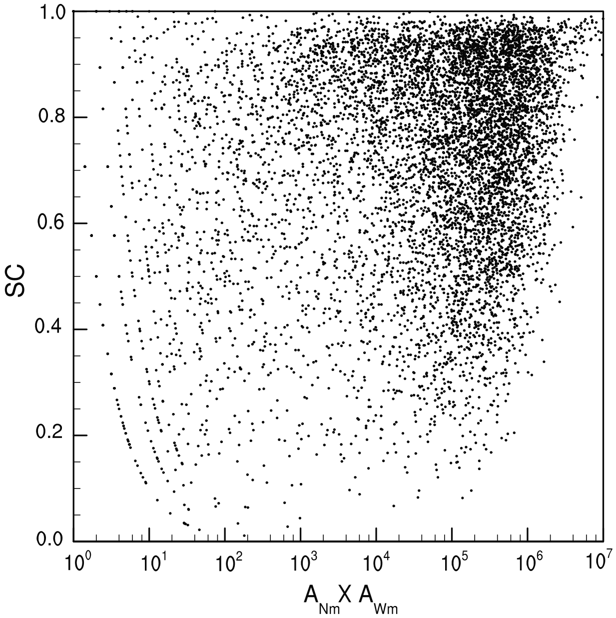

Figure 6. Scatterplot of spatial correlation (as defined in the text) as a function of the geometric mean of the WWLLN and the NLDN autocovariances.

WWLLN diurnal cycle, they cannot fully explain the observed signal and the topic requires further research.

7. Storm Detection Efficiency

[41] As a way to test the WWLLN's ability to capture the electrical-discharge activity on the synoptic and mesoscales, we apply the method proposed by *Jacobson et al.* [2006]. This method is designed to quantify the proportionality of the discharge detection between two networks. When applying *Jacobson et al.*'s [2006] method, it is not expected that the WWLLN will be fully proportional to the NLDN because these two networks are not implemented to detect exactly the same discharges. However, some proportionality between the two networks is expected given the confinement of the overall electrical discharge activity, regardless of its type, to convectively active regions. Some proportionality is also expected because of the overlapping of the two networks in the detection of CG flashes with strong currents.

[42] We group the data of our sample in 3 h bins spanning 0.2° of latitude by 0.2° of longitude. Following the methodology (and nomenclature) of *Jacobson et al.* [2006], we count the number of flashes located in each bin by each network and denominate them as $N_W(j, k, m)$ and $N_N(j, k, m)$, for the WWLLN and NLDN, respectively, with j, k, and m as the indexes for latitude, longitude, and time. We also compute

$$A_{Wm} = \sum_j \sum_k N_W^2(j, k, m) \quad (1)$$

$$A_{Nm} = \sum_j \sum_k N_N^2(j, k, m) \quad (2)$$

$$C_{NWm} = \sum_j \sum_k N_N(j, k, m) N_W(j, k, m), \quad (3)$$

where A_{Wm} and A_{Nm} are the sums of all the bins in the domain for the time m for the WWLLN and the NLDN, respectively. C_{NWm} is the covariance of the networks. The normalized spatial correlation (SC) between the NLDN and WWLLN is the ratio of C_{NWm} to the geometric mean of A_{Nm} and A_{Wm}.

[43] A total of 4098 three hour cases with flashes are contained in our sample. The SC versus the geometric mean of the WWLLN and NLDN autocovariances is shown in Figure 6. The geometric mean of the autocovariances is used as a measure of the overall lightning activity recorded by the networks. Figure 6 shows that the SC can take any value between 0 and 1 and tends to be higher with increasing recorded lightning activity, with a strong clustering of the data toward higher correlation and higher geometric means. This strong relationship is a remarkable result given that the two networks do not measure exactly the same type of discharges. It confirms that the WWLLN data are a source of information with the potential to identify regions of electrical activity on the mesoscale and synoptic scales.

[44] The year 2007–2008 contained 2000 three hour cases with flashes, almost half of those in the sample. This year had a median geometric mean of 68,285, considerably smaller than the medians of 2006–2007 and 2008–2009, 135,132 and 344,144 respectively. The tendency of the spatial correlation to be smaller at smaller geometric means resulted in the year 2007–2008 having the smallest median spatial correlation in the sample, 0.63. The medians for 2006–2007 and 2008–2009 are 0.68 and 0.75, respectively. The strong spatial correlation found indicates that the lightning activity located by both networks is very often occurring within the same region, regardless if the flashes meet our definition of coincident or not. This is evidence that the WWLLN events with no corresponding NLDN event are IC events and not false detections, as previous authors have argued [*Jacobson et al.*, 2006].

[45] An interesting feature of the chosen metric is reflected in the lower left of Figure 6. There, an alignment of dots along curves can be distinguished. This alignment is the result of the occurrence of cases with the same number of flashes in the WWLLN (A_{Wm}) for a different number of flashes in the NLDN (A_{Nm}). When the plotted metric SC is computed for several cases with the same A_{Wm}, the metric is only a function of A_{Nm} and takes the functional form exhibited by the point alignment. For cases with the same A_{Wm}, SC will take on smaller and smaller values as A_{Nm} increases and the correlation relationship between A_{Wm} and A_{Nm} vanishes.

[46] As noted earlier, the WWLLN's overall performance is expected to be better at nighttime. However, the separation of those flashes located during the night from those located during the day is not clear-cut. WWLLN sensors are sparse around the world with distances separating them on the order of thousands of kilometers, frequently spanning across several time zones (Figure 1). The WWLLN requires that at least five sensors identify the same discharge for it to be considered accurately located. This is, for the same discharge, some sensors can be triggered on the daytime side of the world while others involved in its location may be on the nighttime side. For most lightning events, especially those occurring close to dawn or dusk, the generated sferic is likely to be propagated under a mixture of both day and

night Earth-ionosphere waveguides toward the sensors that are used to determine its location.

[47] To evaluate night versus day WWLLN performance, we use the SC statistic described above. We consider those 3 h bins occurring between 1000 and 1600 LT as day cases and those that occurred between 2200 and 0400 LT as night cases. This separation was chosen to exclude from the comparison the time bins with lightning events whose sferics are more likely to be traveling over both the day and night waveguides. This separation leads to 1205 night cases and 934 day cases. The median of the night cases is higher than that for the day cases, 0.74 versus 0.69. Comparison of the two distributions using a rank-sum test gave $P \ll 0.001$, leading us to conclude that the two distributions are indeed different.

8. Summary and Conclusion

[48] The performance of the Worldwide Lightning Location Network (WWLLN), a developing, experimental network increasingly used for applications, is examined. The assessment of the WWLLN capabilities is carried out here by comparing it with the National Lightning Detection Network (NLDN), a network with high DE across the continental United States. Although there have been past efforts to evaluate the WWLLN, they are strongly spatiotemporally limited and outdated. The evaluation campaign here spans from 5 April 2006 to 31 March 2009. Within this time period, the reported flashes in each network from 25°N to 45°N and from 125°W to 75°W are considered.

[49] The capabilities of the network improve strongly from 2006–2007 to 2008–2009, with an overall DE of CG flashes changing from 3.88% in 2006–2007 to 10.30% in 2008–2009. According to an estimate of the IC activity, the DE of all flashes changed from 2.31% to 6.19%, whereas the IC flashes reported the lowest DE of all flash categories changing from 1.78% to 4.82% from 2006–2007 to 2008–2009. The WWLLN DE is found to be strongly dependent on peak current and polarity, reaching values higher than 10% (35%) for currents of ± 35 kA (−130 kA) and stronger. The DE decreases with peak current to reach a minimum of 1.14% for the flashes with peak currents between −3 and −5 kA. LA is found to have northward and westward biases of 4.03 and 4.98 km, respectively.

[50] Despite these encouraging results, the WWLLN has strong limitations. The diurnal cycle is not captured by the network over the continental United States. It shows a diurnal cycle structure with two maxima and with a minimum close to the time of maximum lightning activity (1600 LT). Our analysis shows that the inclusion of oceanic flashes in our domain, the improving density of network sensors, and the WWLLN bias toward stronger flashes explain part, but not all, of this structure. Despite the limitations of the WWLLN, it is found that it has the ability to capture the electrical discharge activity on the mesoscale, with a quantification of the spatial correlation between the WWWLN and the NLDN as high as 0.75 in 2008–2009.

[51] The described capabilities of the WWLLN in its first continental scale and multiyear assessment suggest that different applications could meaningfully use and take advantage of its constantly improving data. However, when using such data caution must be exerted, since the network does have limitations, mainly its low DE and lack of ability to capture the diurnal cycle.

[52] **Acknowledgments.** The authors wish to thank the World Wide Lightning Location Network (http://wwlln.net), a collaboration among over 40 universities and institutions, for providing the lightning location data used in this paper. The National Lightning Detection Network data are provided through the Vaisala Thunderstorm Unit in Tucson, AZ. The authors thank David Vollaro for his help in processing the NLDN data and Robert Holzworth, Erin Lay, Jacob Bortnik, and Ed Zipser for discussions about the diurnal cycle of lightning. Robert Holzworth also provided the authors with valuable information regarding the number of sensors and service dates. The thoughtful comments of three anonymous reviewers improved the quality of the manuscript.

References

Arnone, E., A. Kero, B. M. Dinelli, C.-F. Enell, N. F. Arnold, E. Papandrea, C. J. Rodger, M. Carlotti, M. Ridolfi, and E. Turunen (2008), Seeking sprite-induced signatures in remotely sensed middle atmosphere NO_2, *Geophys. Res. Lett.*, *35*, L05807, doi:10.1029/2007GL031791.

Biagi, C. J., K. L. Cummins, K. E. Kehoe, and E. P. Krider (2007), National Lightning Detection Network (NLDN) performance in southern Arizona, Texas, and Oklahoma in 2003–2004, *J. Geophys. Res.*, *112*, D05208, doi:10.1029/2006JD007341.

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*, 108–122.

Brundell, J. B., C. J. Rodger, and R. L. Dowden (2002), Validation of single station lightning location technique, *Radio Sci.*, *37*(4), 1059, doi:10.1029/2001RS002477.

Carbone, R. E., and J. D. Tuttle (2008), Rainfall occurrence in the U.S. warm season: The diurnal cycle, *J. Clim.*, *21*, 4132–4146.

Carbone, R. E., J. D. Tuttle, D. Ahijevych, and S. B. Trier (2002), Inferences of predictability associated with warm season precipitation episodes, *J. Atmos. Sci.*, *59*, 2033–2056.

Carey, L. D., S. A. Rutledge, and W. A. Petersen (2003), The relationship between severe storm reports and cloud-to-ground lightning polarity in the contiguous United States from 1989 to 1998, *Mon. Weather. Rev.*, *131*, 1211–1228.

Cummins, K. L., and M. J. Murphy (2009), An overview of lightning locating systems: History, techniques, and data uses, with an in-depth look at the U.S. NLDN, *IEEE Trans. Electromagn. Compat.*, *51*(3), 499–518.

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, doi:10.1029/98JD00153.

De Souza, P. E., O. Pinto Jr., I. R. C. A. Pinto, N. J. Ferreira, and A. F. dos Santos (2008), The intracloud/cloud-to-ground lightning ratio in Southeastern Brazil, *Atmos. Res.*, *91*, 491–499.

Dowden, R. L., J. B. Brundell, and C. J. Rodger (2002), VLF lightning location by time of group arrival (TOGA) at multiple sites, *J. Atmos. Sol. Terr. Phys.*, *64*, 817–830.

Fleenor, S. A., C. J. Biagi, K. L. Cummins, E. P. Krider, and X. M. Shao (2009), Characteristics of cloud-to-ground lightning in warm season thunderstorms in the Central Great Plains, *Atmos. Res.*, *91*(2–4), 333–352, doi:10.1016/j.atmosres.2008.08.011.

Idone, V. P., D. A. Davis, P. K. Moore, Y. Wang, R. W. Henderson, M. Ries, and P. F. Jamason (1998b), Performance evaluation of the National Lightning Detection Network in eastern New York. Part II: Location accuracy, *J. Geophys. Res.*, *103*(D8), 9057–9069, doi:10.1029/98JD00155.

Idone, V. P., D. A. Davis, P. K. Moore, Y. Wang, R. W. Henderson, M. Ries, and P. F. Jamason (1998a), Performance evaluation of the National Lightning Detection Network in eastern New York. Part I: Detection efficiency, *J. Geophys. Res.*, *103*(D8), 9045–9055, doi:10.1029/98JD00154.

Jacobson, A. R., R. Holzworth, J. Harlin, R. Dowden, and E. Lay (2006), Performance assessment of the Worldwide Lightning Location Network (WWLLN) using the Los Alamos Sferic Array (LASA) array as ground-truth, *J. Atmos. Oceanic Technol.*, *23*, 1082–1092.

Jerauld, J., V. A. Rakov, M. A. Urman, K. J. Rambo, D. M. Jordan, K. L. Cummins, and J. A. Cramer (2005), An evaluation of the performance characteristics of the U.S National Lightning Detection Network in Florida using rocket-triggered lightning, *J. Geophys. Res.*, *110*, D19106, doi:10.1029/2005JD005924.

Lay, E. H., R. H. Holzworth, C. J. Rodger, J. N. Thomas, O. Pinto, and R. L. Dowden (2004), WWLL global lightning detection system: Regional validation study in Brazil, *Geophys. Res. Lett.*, *31*, L03102, doi:10.1029/2003GL018882.
Lay, E. H., A. R. Jacobson, R. H. Holzworth, C. J. Rodger, and R. L. Dowden (2007), Local time variation in land/ocean lightning flash density as measured by the World Wide Lightning Location Network, *J. Geophys. Res.*, *112*, D13111, doi:10.1029/2006JD007944.
Lucas, C., and R. E. Orville (1996), TOGA COARE: Oceanic lightning, *Mon. Weather. Rev.*, *124*, 2077–2082.
Lyons, W. A., M. Uliasz, and T. E. Nelson (1998), Large peak current cloud-to-ground lightning flashes during the summer months in the contiguous United States, *Mon. Weather. Rev.*, *126*, 2217–2233.
Mackerras, D., M. Darveniza, R. E. Orville, E. R. Williams, and S. J. Goodman (1998), Global lightning: Total, cloud and ground flash estimates, *J. Geophys. Res.*, *103*(D16), 19,791–19,809, doi:10.1029/98JD01461.
Nesbitt, S. W., and E. J. Zipser (2003), The diurnal cycle of rainfall and convective intensity according to three years of TRMM measurements, *J. Clim.*, *16*, 1456–1474.
Ortega, P. (2007), A three magnetic direction finder network for a local warning device, *J. Light. Res.*, *2*, 18–27.
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*, 1179–1193.
Pessi, A., S. Businger, K. L. Cummins, N. W. S. Demetriades, M. Murphy, and B. Pifer (2009), Development of a Long-Range Lightning Detection Network for the Pacific: Construction, Calibration, and Performance, *J. Atmos. Oceanic Technol.*, *26*, 145–166.
Petersen, W. A., S. A. Rutledge, and R. E. Orville (1996), Cloud-to-ground lightning observations from TOGA COARE: Selected results and lightning location algorithms, *Mon. Weather Rev.*, *124*, 602–620.
Price, C., Y. Yair, and M. Asfur (2007), East African lightning as a precursor of Atlantic hurricane activity, *Geophys. Res. Lett.*, *34*, L09805, doi:10.1029/2006GL028884.
Rivas, L. S., and F. de Pablo (2007), Total flash density and the intracloud/cloud-to-ground lightning ratio over the Iberian Peninsula, *J. Geophys. Res.*, *112*, D13114, doi:10.1029/2006JD007624.
Rodger, C. J., J. B. Brundell, R. H. Holzworth, and E. H. Lay (2009), Growing detection efficiency of the World Wide Lightning Location Network. Coupling of thunderstorms and lightning discharges to near-Earth space, Proceedings of the Workshop, Corte (France), 23–27 June 2008, 1118, 15–20, doi:10.1063/1.3137706.
Rodger, C. J., J. B. Brundell, and R. L. Dowden (2005), Location accuracy of VLF Worldwide Lightning Location (WWLL) network: Post-algorithm upgrade, *Ann. Geophys.*, *23*, 277–290.
Rodger, C. J., J. B. Brundell, R. L. Dowden, and N. R. Thomson (2004), Location accuracy of long distance VLF lightning location network, *Ann. Geophys.*, *22*, 747–758.
Rodger, C. J., S. Werner, J. B. Brundell, E. H. Lay, N. R. Thomson E. H. Lay, R. H. Holzworth, and R. L. Dowden (2006), Detection efficiency of the VLF Worldwide Lightning Location Network (WWLLN): Initial case study, *Ann. Geophys.*, *24*, 3197–3214.
Steiger, S. M., and R. E. Orville (2002), Cloud-to-ground lightning characteristics over Houston, Texas: 1989–2000, *J. Geophys. Res.*, *107*(D11), 4117, doi:10.1029/2001JD001142.
Steiger, S. M., and R. E. Orville (2003), Cloud-to-ground lightning enhancement over Southern Louisiana, *Geophys. Res. Lett.*, *30*(19), 1975, doi:10.1029/2003GL017923.
Suszcynsky, D. M., M. W. Kirkland, A. R. Jacobson, R. C. Franz, S. O. Knox, J. L. L. Guillen, and J. L. Green (2000), FORTE observations of simultaneous VHF and optical emissions from lightning: Basic phenomenology, *J. Geophys. Res.*, *105*(D2), 2191–2201, doi:10.1029/1999JD900993.
Watt, A. D. (1967), VLF Radio Engineering, in *Electromagnetic Waves*, *Int. Ser. Monogr.*, *14*, p. 703, Pergamon, Oxford.
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*, 999–1019.
Zipser, E. J., D. J. Cecil, C. Liu, S. W. Nesbitt, and D. P. Yorty (2006), Where are the most intense thunderstorms on Earth?, *Bull. Am. Meteorol. Soc.*, *87*, 1057–1071.

S. F. Abarca and K. L. Corbosiero, Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, 405 Hilgard Ave., Los Angeles, CA 90095, USA. (abarcas@atmos.ucla.edu)

T. J. Galarneau Jr., Department of Atmospheric and Environmental Sciences, University at Albany/State University of New York, Albany, NY 12222, USA.