GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 2344–2348, doi:10.1002/grl.50428, 2013

Evaluating WWLLN performance relative to TRMM/LIS

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Received 8 March 2013; revised 27 March 2013; accepted 27 March 2013; published 28 May 2013.

[1] This study evaluates 4 years (2009–2012) of World Wide Lightning Location Network (WWLLN) data relative to the Tropical Rainfall Measuring Mission Lightning Imaging Sensor (LIS). In the Western Hemisphere, between 38°N and 38°S, the WWLLN detection efficiency (DE) (of LIS flashes) steadily improves from 6% during 2009 to 9.2% during 2012. The WWLLN is approximately three times more likely to detect a LIS flash over the ocean (17.3%) than over land (6.4%), and DE values greater than 20% only occur over the oceans. An average of 1.5 WWLLN strokes occurs during each matched LIS flash, but 71.5% of matched flashes are single stroke. Matched LIS flashes have more events/groups, longer durations, and larger areas than non-matched flashes. The close spatial proximity (11 km) and temporal proximity (+62 ms) between matched WWLLN and LIS flashes are important for Geostationary Lighting Mapper risk reduction studies that use existing networks to develop proxy data sets. **Citation:** Rudlosky, S. D., and D. T. Shea (2013), Evaluating WWLLN Performance Relative to TRMM/LIS, *Geophys. Res. Lett.*, *40*, 2344–2348, doi:10.1002/grl.50428.

1. Introduction

[2] Ground-based lightning detection networks are continuously improving and growing in importance to scientists and operational weather forecasters. As the variety of users expands, it becomes increasingly important to understand the detection capabilities of these networks. The ground-based World Wide Lightning Location Network (WWLLN) detects very low frequency (VLF) radio waves emitted by lightning [*Dowden et al.*, 2002; *Rodger et al.*, 2004]. It is most sensitive to cloud-to-ground (CG) flashes since they radiate strongest in the VLF range. This study evaluates the detection efficiency (DE), location and timing differences, and multiplicity of WWLLN strokes relative to total lightning observations from the satellite-based Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor (LIS).

[3] The LIS is an optical transient detector that identifies lightning flashes by detecting the discrete optical pulses associated with changes in cloud brightness at each pixel [*Christian et al.*, 1992]. It reports the time, location, and radiant energy of total lightning events (e.g., CG and intracloud (IC) [*Christian et al.*, 1999]. IC and CG flashes emit very similar optical pulses, so both types are readily observed from above [*Christian et al.*, 1992]. Individual lightning events (illuminated pixels) are combined into groups, flashes, and areas using optical pulse-to-flash and flash-to-cell clustering algorithms [*Boccippio et al.*, 2002]. LIS observations have been cross-calibrated with ground-based lightning detection networks [e.g., *Thomas et al.*, 2000; *Ushio et al.*, 2002] and used to create global lightning climatologies [e.g., *Christian et al.*, 1999; *Cecil et al.*, 2012].

[4] This study compares 4 years (2009–2012) of WWLLN and LIS data within the LIS field of view (38°N and 38°S) in the Western Hemisphere (0° to −180°W). This domain represents overlapping coverage between the LIS and the planned operational Geostationary Lightning Mapper (GLM) [*Goodman et al.*, 2013]. We document the present WWLLN performance and illustrate how it varies in space and time. Improved understanding of WWLLN detection capabilities will enhance its use in research and operations. This study aims to provide valuable information on the relationship between ground-based and satellite-based lightning observations, which will become more important as the GLM launch approaches.

2. Data and Methods

2.1. Data

[5] Four years (2009–2012) of WWLLN and LIS data were gathered. Note that the WWLLN (sferics) and LIS (optics) detect different aspects of a lightning flash and that this study compares WWLLN "strokes" with LIS "flashes." WWLLN strokes occur at a discrete time and place, while LIS flashes have durations (tens to hundreds of milliseconds) and areal extents (tens to hundreds of square kilometers). Furthermore, the WWLLN continuously detects mainly CG lightning, whereas the polar-orbiting LIS provides ~90 s snapshots of all types of lightning within its field of view (600 × 600 km) [*Christian et al.*, 1999]. Despite these differences, the LIS is used as a benchmark because it has provided consistent lightning observations with high DE since its launch in 1997.

[6] The WWLLN began with 11 sensors during 2003 [*Lay et al.*, 2004] and steadily increased to more than 70 sensors by January 2013 [*Hutchins et al.*, 2013]. It monitors the VLF radio waves (sferics) emitted by lightning and uses a time of group arrival technique to locate lightning strokes [*Dowden et al.*, 2002]. Global coverage requires relatively few sensors because VLF radio waves travel through the earth ionosphere waveguide with minimal attenuation [*Crombie*, 1964; *Dowden et al.*, 2002; *Rodger et al.*, 2004]. WWLLN performance has improved over time due to an increase in the number of sensors [*Abarca et al.*, 2010] and improvements in waveform processing algorithms [*Rodger et al.*, 2009]. *Abarca et al.* [2010] evaluated WWLLN performance relative to the National Lightning

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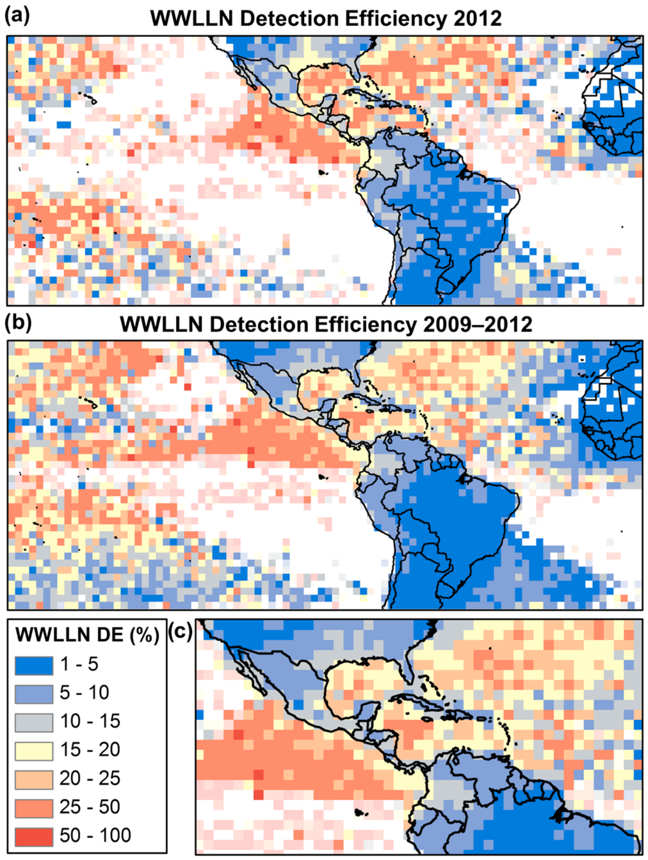

Figure 1. Spatial distribution of WWLLN DE during 2012 (a) and during 2009–2012 (b and c). DE is computed by dividing the sum of the matched LIS flashes by the sum of all LIS flashes within 2° × 2° grid cells. The brightness is reduced for grid cells with fewer than 15 LIS flashes, and white areas indicate grid cells with no LIS flashes.

Detection Network and estimated that the WWLLN detected 10.3% of CG flashes and 6.19% of all flashes in the continental United States during 2008–2009. Studies have shown that WWLLN DE is greater for stronger CG flashes (i.e., greater peak current) [*Jacobson et al.*, 2006; *Lay et al.*, 2007; *Rodger et al.*, 2009] and that the WWLLN typically detects a single stroke within each flash [*Rodger et al.*, 2004, 2005; *Jacobson et al.*, 2006].

[7] The TRMM LIS was launched into low earth orbit (350 km) in November 1997, providing coverage between 38°N and 38°S [*Christian et al.*, 1999]. Its orbit was subsequently boosted to ~400 km in 2001 to increase mission lifetime, with no impact on DE [*Cecil et al.*, 2012]. The LIS is an optical detector that measures transient changes in cloud brightness caused by lightning. Flashes are defined by grouping the optical events based on space and time criteria [*Christian et al.*, 1999]. Optical pulse-to-flash clustering algorithms combine illuminated pixels (events) into groups and groups into flashes. The estimated LIS flash DE is ~90% at night and ~70% at local noon [*Boccippio et al.*, 2002; *Cecil et al.*, 2012]. Both the LIS and WWLLN exhibit diurnal DE variability that the present study does not address. Although this diurnal variability is outside the scope of our general analysis, it should be considered for more focused applications. The TRMM has a low-altitude, low-inclination orbit that precesses through the local diurnal cycle [*Simpson et al.*, 1988], reducing the impact of diurnal DE variability on annual lightning climatologies. Although the LIS only samples while overhead, approximately 0.1% of the time in the tropics, this is sufficient to produce accurate annual climatologies [*Christian et al.*, 1999; 2003].

2.2. Methods

[8] Previous comparisons of ground-based and satellite-based lightning observations have used both flash density comparisons [e.g., *Boccippio et al.*, 2001] and more complex flash-by-flash comparisons [e.g., *Thomas et al.*, 2000; *Ushio et al.*, 2002]. This study matches individual LIS flashes and WWLLN strokes to accurately determine the relative WWLLN DE and allow for computation of higher-order parameters. Our analysis assumes that the LIS observes all lightning flashes in its field of view, and no attempt was made to correct for diurnal DE variability.

[9] Several time and distance thresholds were examined to determine the best matching criteria for estimating the fraction of LIS flashes detected by the WWLLN. Outside

Table 1. Relative DE in the Western Hemisphere Between 38°N and 38°S During 2009–2012[a]

	Overall	Land	Ocean	North America	South America
2009	6.0	4.0	12.3	8.0	2.3
2010	6.8	4.8	13.9	7.6	4.1
2011	8.1	5.8	15.2	8.7	4.8
2012	9.2	6.4	17.3	10.7	4.9
2009–2012	7.5	5.2	14.7	8.7	4.0

[a] DE is computed by dividing the sum of the matched LIS flashes by the sum of all LIS flashes within each region and time period.

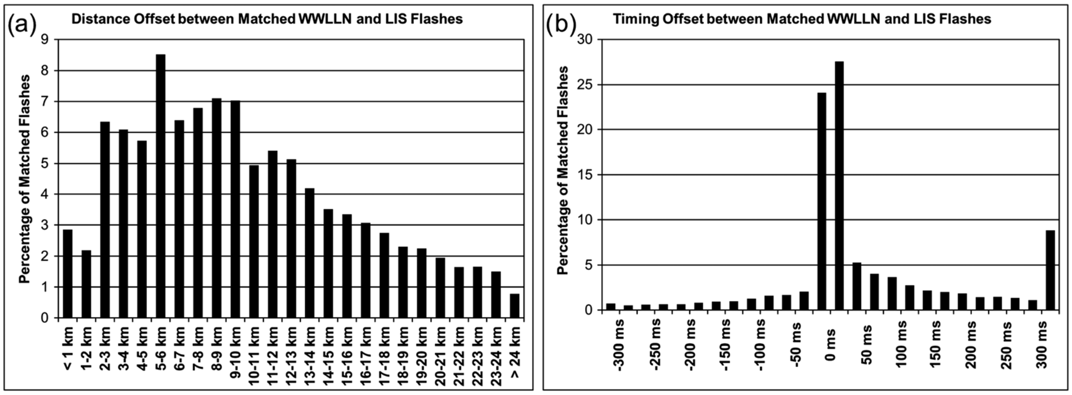

Figure 2. Distance (a) and timing (b) offsets between the 182,310 matched WWLLN and LIS flashes (2009–2012). The average (median) distance and time offsets are 11 km (10 km) and +62 ms (0 ms), respectively. Note that the upper limits are open in each panel (final columns) because WWLLN strokes can occur greater than 25 km from the radiance-weighted LIS centroid (i.e., within 25 km of any group) and longer than 300 ms into a LIS flash.

of very tight spatial (1 km) and temporal (50 ms) thresholds, changing the matching criteria produced very small differences. We selected broad distance (25 km) and time (330 ms) thresholds to ensure that all matches were identified. For flashes to be considered a match, the WWLLN stroke must have occurred within 25 km of any group in a LIS flash and within 330 ms before, during, or after a LIS flash. Our spatial and temporal matching criteria required additional caution to avoid double counting. The WWLLN DE (relative to the LIS) is computed by dividing the sum of the matched LIS flashes by the sum of all LIS flashes within 2° × 2° grid cells (Figure 1).

[10] In addition to the relative DE, flash-by-flash comparisons reveal the location and timing differences between matched flashes, the number of WWLLN strokes associated with each matched LIS flash (i.e., multiplicity), and the LIS characteristics of matched and unmatched flashes. The following sections describe the spatial and temporal distributions of WWLLN performance relative to the LIS and discuss 2012 performance statistics unless otherwise noted.

3. Results

[11] World Wide Lightning Location Network performance improves each year between 2009 and 2012. Within the Western Hemisphere (between 38°N and 38°S), the LIS detects ~600,000 flashes each year, while the number of WWLLN strokes increases from ~60 million during 2009 to more than 100 million during 2012. Table 1 quantifies the improving WWLLN performance. The Western Hemisphere relative DE increases from 6% during 2009 to 9.2% during 2012, and improving performance is evident in each of the geographical subdomains (e.g., North America). Despite the overall improvement, variability exists in the relative DE distributions.

[12] The dominant spatial feature is a clear contrast in DE between the continental and oceanic regions (Figure 1). The WWLLN DE is approximately three times greater over the oceans than over land (Table 1), and areas with DE greater than 20% occur exclusively over the oceans. Studies have shown a tendency for stronger (but fewer) flashes over the oceans than over land [e.g., *Biswas and Hobbs*, 1990; *Orville and Huffines*, 2001; *Rudlosky and Fuelberg*, 2010; *Orville et al.*, 2011; *Said et al.*, 2013; *Hutchins et al.*, 2013]. Since the WWLLN DE increases with increasing peak current [*Jacobson et al.*, 2006; *Abarca et al.*, 2010], the greater proportion of strong CG flashes over the oceans helps explain the greater DE. Additional research is required to specify the meteorological and technological contributions to this observation. This research will become increasingly important as meteorological applications requiring knowledge of thunderstorm occurrence over the oceans continue to expand [e.g., *Pessi and Businger*, 2009; *DeMaria and DeMaria*, 2009].

[13] World Wide Lightning Location Network performance also differs between North America and South America (Table 1). The WWLLN performs twice as well over North America (10.7%) than over South America (4.9%), but the improving performance is more pronounced over South America (up ~100%) than over North America (up ~25%). There are fewer WWLLN sensors in South America than in North America [*Virts et al.*, 2013], which helps explain the smaller DE. Meteorological variability also may contribute to this observation, but further research will be required to understand its influence.

[14] The location and timing differences between matched LIS and WWLLN flashes provide additional performance metrics. For this comparison, LIS flashes are defined by their initiation time and radiance-weighted centroid. The centroid is used since a WWLLN stroke can occur within 25 km of multiple LIS groups. Figure 2 displays the distance (Figure 2a) and timing (Figure 2b) offsets between matched WWLLN and LIS flashes. The average (median) distance

Table 2. Average Characteristics of LIS Flashes Observed (Matched) and Not Observed (Not Matched) by the WWLLN[a]

	Matched	Not Matched
Groups (count)	15.7 ± 0.04	10.7 ± 0.01
Events (count)	97.8 ± 0.31	44.1 ± 0.04
Duration (ms)	25.1 ± 0.9	9.0 ± 0.2
Area (km^2)	580.7 ± 1.33	254.3 ± 0.17
MNEG	20.5 ± 0.05	9.0 ± 0.01
MGA (km^2)	502.1 ± 1.23	225.6 ± 0.16

[a] The MNEG and MGA were introduced by *Koshak* [2010] as potential return stroke detectors (i.e., CG identifiers).

between matched WWLLN and LIS locations is 11 km (10 km), which is well within the average horizontal extent of a LIS flash (Table 2) and agrees with previously reported accuracies of both the WWLLN [*Jacobson et al*., 2006; *Abarca et al*., 2010] and LIS [*Thomas et al*., 2000]. Most matched WWLLN flashes occur within ±25 ms of LIS flash initiation (Figure 2b). This suggests that our temporal matching criteria could be tightened, but this would increase the risk of missing some true matches. Note the slight tendency toward positive values in Figure 2b (signifying that the WWLLN stroke occurred during the LIS flash) and that the average (median) offset is +62 ms (0 ms). Since these networks detect different aspects of a lightning flash (i.e., optics versus sferics), the proximity of matched flashes is important for GLM risk reduction activities (e.g., developing proxy GLM data sets).

[15] Multiple WWLLN strokes occur during some LIS flashes. Although 71.5% of matched flashes have a single WWLLN stroke, the average number of WWLLN strokes per LIS flash (multiplicity) is 1.5 during 2009–2012. Furthermore, the multiplicity increases concurrently with improving DE, from 1.4 during 2009 to 1.6 during 2012 (not shown). On average, the subsequent WWLLN strokes occur 70 ms and 7 km apart. Several factors likely contribute to the occurrence of multiple WWLLN strokes during individual LIS flashes. For example, the WWLLN likely detects some multistroke flashes, the LIS optical pulse-to-flash clustering thresholds could be too loose, or our matching criteria might be too broad. Since each of these factors likely contributes to average multiplicities greater than 1, future studies should seek to determine their relative influences.

[16] Our analysis also reveals that the WWLLN detects the strongest LIS flashes and provides further evidence that it detects mainly CG flashes. Table 2 compares the average characteristics of LIS flashes observed by the WWLLN (matched) with those not observed by the WWLLN (not matched). Matched LIS flashes have more events and groups, longer durations, and larger average areas than non-matched flashes, so they are more likely to be CG than IC. *Koshak* [2010] introduced the maximum number of events per group (MNEG) and maximum group area (MGA) as potential return stroke identifiers (i.e., CG versus IC) and showed that for large samples these variables can be used to estimate the IC:CG ratio. Since MNEG and MGA are both larger for the matched LIS flashes (Table 2), they are more likely to contain return strokes (i.e., CG flashes) than the non-matched flashes.

4. Summary

[17] This study compared 4 years (2009–2012) of data from the WWLLN and TRMM LIS. We determined the fraction of LIS flashes that were detected by the WWLLN to improve our understanding of WWLLN detection capabilities and enhance its use in research and operations. The results provide valuable information on the relationship between ground-based and satellite-based lightning observations, which will become increasingly important as the GLM launch approaches.

[18] We described both the spatial variability and the temporal variability of WWLLN performance. The WWLLN DE (relative to the LIS) steadily improved from 6% during 2009 to 9.2% during 2012 (i.e., in the Western Hemisphere, between 38°N and 38°S). Improving performance also was evident in each of the geographical subdomains (i.e., North America, South America, land, and oceans). The WWLLN was approximately three times more likely to detect LIS flashes that occurred over the oceans (17.3%) than over land (6.4%), and DEs greater than 20% occurred exclusively over the oceans. It performed twice as well over North America (10.7%) than over South America (4.9%). Further research will be required to investigate the meteorological and technological contributions to these observations.

[19] An average of 1.5 WWLLN strokes occurred during each matched LIS flash, but 71.5% of matched flashes were single stroke. Multiple WWLLN strokes during individual LIS flashes suggest that the WWLLN detected multistroke flashes, the LIS optical pulse-to-flash clustering thresholds were too loose, or our distance (25 km) and time (330 ms) thresholds should be tightened. Each of these factors could have contributed to multiplicities greater than 1, but future research will be required to determine their relative influences.

[20] Our analysis revealed that the WWLLN preferentially detects the strongest LIS flashes (i.e., those with more groups and events, longer durations, and larger horizontal extents). Both the MNEG and the MGA were larger for the matched LIS flashes than the non-matched flashes, so the matched flashes were more likely to contain return strokes (i.e., CG flashes). Since these networks detect different aspects of a lightning flash (i.e., optics versus sferics), the close spatial proximity (11 km) and temporal proximity (+62 ms) of matched flashes are encouraging for GOES-R risk reduction studies. Findings also suggest that the WWLLN will benefit post-launch GLM validation (i.e., characterizing its DE and location accuracy), especially over the oceans.

[21] **Acknowledgments.** Funding for this project was provided by NOAA/NESDIS through the Cooperative Institute for Climate and Satellites. The authors wish to thank the World Wide Lightning Location Network (http://wwlln.net), a collaboration among over 50 universities and institutions, for providing the lightning location data used in this paper. We also thank the Lightning and Atmospheric Electricity Group at NASA's Marshall Space Flight Center for their support of the TRMM/LIS archive and two anonymous reviewers for their insights. The contents of this paper are solely the opinions of the authors and do not constitute a statement of policy, decision, or position on behalf of NOAA or the U.S. Government.

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