

Evaluating Ground-Based Lightning Detection Networks using TRMM/LIS Observations

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Abstract — Lightning detection networks observe lightning flashes at various spatial and temporal scales, and weather forecasters are increasingly using this information to monitor convective weather patterns. The planned GOES-R Geostationary Lightning Mapper (GLM) will detect intra-cloud and cloud-to-ground lightning with nearly uniform performance in both space and time. The GLM will provide data at spatial and temporal scales that are currently unavailable, so existing networks must be used to simulate future capabilities. This paper briefly introduces multi-scale lightning observations, and describes the performance of select ground-based lightning detection networks. Data from the Global Lightning Dataset 360 (GLD360), World Wide Lightning Location Network (WWLLN), and Earth Networks Total Lightning Network (ENTLN) are evaluated relative to the Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor (LIS). Direct flash-by-flash comparisons allow analysis of the relative detection efficiency of each network (i.e., assuming LIS is truth). This information will help lightning vendors better characterize their network performance, and will provide forecasters with important insights as the operational use of lightning data continues to grow.

Keywords—Lightning, remote sensing, GLM

I. INTRODUCTION

Many meteorological applications use lightning observations from both ground- and space-based lightning detection networks. These continuously improving networks detect optical and radiometric emissions from lightning, and their data are 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. This study evaluates the detection efficiency (DE) of several ground-based networks (GBN) relative to total lightning observations from the satellite-based Tropical Rainfall Measuring Mission (TRMM) Lightning Image Sensor (LIS). We document the present GBN performance and illustrate how it varies in space and time. Improved understanding of these GBN detection capabilities will enhance their use in weather research and operations. This study aims to provide valuable information on the relationship between ground- and satellite-based lightning observations, which will become even more important in the GOES-R

Geostationary Lightning Mapper (GLM) era. Each of the GBN has strengths and weaknesses in terms of detection efficiency and location accuracy, types of lightning detected, and areal coverage, but this paper does not attempt to quantify or explain any differences between the networks.

II. DATA AND METHODS

The study domain is the LIS field of view (38° N to 38° S) in the Western Hemisphere (0° to -180° W), which is the region of overlapping coverage between LIS and the planned GOES-R GLM [1]. Note that the GBNs (radiometric) and LIS (optical) detect different aspects of a lightning flash, and that this study compares GBN “strokes” with LIS “flashes”. The GBN strokes occur at a discrete time and place, while LIS flashes have durations (10’s to 100’s of ms) and areal extents (10’s to 100’s of km^2). Furthermore, the GBNs continuously detect mostly cloud-to-ground (CG) lightning, whereas the low-earth orbiting LIS provides ~ 90 sec snapshots of total lightning within its field of view (600×600 km; [2]). Despite these differences, the LIS is used as a benchmark because it has provided continuous total lightning observations with high detection efficiency since its launch in 1997.

The LIS is an optical detector which measures changes in cloud brightness caused by lightning [2]. It reports the time, location, and radiant energy of total lightning events (i.e., intra-cloud and CG discharges; [2]). Individual lightning events (illuminated pixels) are combined into groups, flashes, and areas using optical pulse-to-flash and flash-to-cell clustering algorithms [3]. Flashes are defined by grouping the optical events based on space and time criteria [2]. The estimated LIS flash DE is $\sim 90\%$ at night and $\sim 70\%$ at local noon [3, 4]. Intra-cloud (IC) and CG flashes emit very similar optical pulses, so both types are readily observed from above [5]. TRMM has a low-altitude, low-inclination orbit that precesses through the local diurnal cycle [6], reducing the impact of diurnal DE variability on the lightning distributions. Although LIS only samples while overhead, approximately 0.1% of the time in the tropics, this is sufficient to produce accurate annual climatologies [2, 7].

The ground-based World Wide Lightning Location Network (WWLLN) detects very-low frequency (VLF) radio waves emitted by lightning [8, 9]. The WWLLN is most

sensitive to CG flashes since they radiate strongest in the VLF range [9]. It began with 11 sensors during 2003 [10] and steadily increased to more than 70 sensors by January 2013 [11]. The WWLLN monitors VLF radio waves between 3-30 kHz emitted by lightning, and uses a time of group arrival (TOGA) technique to locate lightning strokes [8]. Global coverage requires relatively few sensors because VLF radio waves travel through the Earth-ionosphere waveguide with minimal attenuation [8, 9, 12]. The WWLLN performance has improved over time due to an increase in the number of sensors [13] and improvements in waveform processing algorithms [14]. In the Western Hemisphere between 38° N and 38° S, WWLLN detection efficiency (of LIS flashes) steadily improved from 6% during 2009 to 9.2% during 2012 [15]. They found that WWLLN was ~3 times more likely to detect a LIS flash over the ocean (17.3%) than over land (6.4%), and detection efficiencies greater than 20% occurred only over the oceans.

The following description paraphrases [16] to introduce the Earth Networks Total Lightning Network (ENTLN). The ENTLN combines advanced lightning detection technologies with modern electronics to monitor total lightning activity. It uses a wideband sensor with detection frequency ranging from 1 Hz to 12 MHz. The wide frequency range enables the sensor to detect strong CG strokes, as well as weaker IC pulses. When lightning occurs, electromagnetic energy is emitted in all directions; many ENTLN sensors detect and record the waveforms, and then send the waveforms to a central server via the Internet. The arrival times are calculated by correlating the waveforms from all sensors that detect the strokes of a flash. The waveform arrival time and signal amplitude are used to determine the stroke type (IC or CG), polarity, peak current, and location including latitude, longitude, and altitude. Rather than using only the peak pulse times, the ENTLN uses complete waveforms for locating flashes and differentiating between IC and CG strokes. Strokes are clustered into a flash if they are within 700 milliseconds and 10 km. The ENTLN provides global coverage, but their high density network covers CONUS, Alaska, Hawaii, the Caribbean basin, Australia, and Brazil.

The Global Lightning Dataset 360 (GLD360) is a long-range lightning detection network developed and operated by Vaisala, Inc. The network's ground-based sensors detect the VLF radio waves emitted by lightning [17]. The network determines the distance of propagation and time of arrival by correlating the shape of the received waveform with those contained in the sensor's bank of expected waveforms [17]. Each sensor has its own bank of predetermined waveforms, which are catalogued by day/night profile and distance. Lightning discharges primarily are located using the arrival time, but also using a combination of arrival azimuth angle, estimated range, and estimated amplitude [17]. Since CG lightning emits more strongly in the VLF range than IC lightning [18], the GLD360 detects primarily CG lightning. The network also detects some strong IC pulses, but does not distinguish between CG and IC. The GLD360 reports the timing and location of lightning strokes, as well as the polarity and estimated peak current [17, 19]. The GLD360 was the first global GBN to estimate peak current for all detected individual

return strokes [17]. Note that a data access agreement restricts our GLD360 analysis to between 38° N and 25° S (versus 38° N to 38° S for WWLLN and ENTLN).

This study matches individual LIS flashes with WWLLN/GLD360/ENTLN strokes using the methods described by [15]. Our analysis assumes that LIS observes all lightning flashes in its field of view, and no attempt was made to correct for diurnal variability in LIS DE. Several time and distance thresholds were examined to determine the best matching criteria for estimating the fraction of LIS flashes detected by the GBNs. Outside of very tight spatial (1 km) and temporal thresholds (50 ms), changing the matching criteria produced very small differences. We selected relatively broad distance (25 km) and time (330 ms) thresholds to ensure that all matches were identified. For flashes to be considered a match, the GBN 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. These somewhat liberal spatial and temporal matching criteria required additional caution to avoid double counting. Maps of relative DE are computed by dividing the sum of the "matched" LIS flashes (i.e., those seen by the GBNs) by the sum of "all" LIS flashes within 2°×2° grid cells.

III. RESULTS

During 2012 in our domain, WWLLN observed ~110 million strokes, ENTLN detected ~413 million strokes, and GLD360 reported ~285 million strokes (Table 1). Figure 1 illustrates the (a) LIS flash density, (b) WWLLN stroke count, (c) ENTLN stroke count, and (d) GLD360 stroke count. Each map resembles the many previously published lightning climatologies, and each of the GBNs shows similar spatial patterns. The GBNs have greatest densities in North and Central America, whereas LIS has greatest densities in Central and South America. Table 1 shows that the LIS observed 646 999 flashes in the WWLLN/ENTLN domain and 520 720 in the GLD360 domain during 2012. The WWLLN, ENTLN, and GLD360 detected 59 242, 181 044, and 131 742 of those flashes, respectively (Table 1).

TABLE I. THE WWLLN, ENTLN, AND GLD360 STROKE COUNTS, LIS FLASH COUNT, MATCHED LIS FLASH COUNT, AND RELATIVE DE IN THE WESTERN HEMISPHERE FOR EACH NETWORK. NOTE THAT OUR GLD360 DOMAIN EXTENDS ONLY TO 25° S (VERSUS 38° S FOR WWLLN AND ENTLN).

	WWLLN	ENTLN	GLD360
Strokes/Flashes	110,089,510	413,376,293	284,893,233
LIS Flashes	646,999	646,999	520,720
Matched	59,242	181,044	131,742
Relative DE	9.2	28.0	25.3

The WWLLN detects 9.2% of all LIS flashes (Table 2), the ENTLN detects 28.0%, and the GLD360 detects 25.3%. Table 2 and Fig. 2 illustrate the spatial and temporal variability in the relative DE distributions, revealing greatest values over North America, with the exception of the WWLLN. That network exhibits a clear contrast in DE between the continental and oceanic regions (Fig. 2a), with DE greater than 20% occurring exclusively over the oceans. Studies have shown a tendency

for stronger (but fewer) flashes over the oceans than over land [e.g., 11, 19, 20, 21, 22, 23]. Since WWLLN DE increases with increasing peak current [13, 24], the greater proportion of strong CG flashes over the oceans helps explain the greater DE. WWLLN detects 17.3% of all LIS flashes over the oceans (in our domain; Table 2), with most oceanic grid cells having relative DE values exceeding 15% (Fig. 2a). Note that in Fig. 2 white grid cells have no LIS flashes, and grid cells with less than 15 LIS flashes are reduced in brightness to illustrate the reduced confidence in DE estimates from those areas (i.e., exclusively over the oceans).

TABLE II. THE REGIONAL RELATIVE DE FOR EACH NETWORK. NOTE THAT NORTH AMERICA INCLUDES ALL FLASHES THAT OCCURRED OVER THE LAND MASSES OF NORTH AMERICA, CENTRAL AMERICA, AND THE CARIBBEAN, WHEREAS SOUTH AMERICA INCLUDES ALL FLASHES THAT OCCURRED OVER THAT LANDMASS.

	WWLLN	ENTLN	GLD360
W. Hemisphere	9.2	28.0	25.3
North America	10.7	60.1	33.4
South America	4.9	11.3	17.5
Oceans	17.3	35.6	33.0

The ENTLN and GLD360 have large regions with relative DE greater than 25% (Figs. 2b, 2c), with no clear contrast between land and ocean. Examining Table 2 and Fig. 2 side-by-side reveals that the average regional values can cover up important spatial distributions. For example, the GLD360 detects 17.5% of LIS flashes in South America (north of 25° S), with better performance to the west and grid cell values generally exceeding 15%. The ENTLN detects 11.3% of LIS flashes in South America (north of 38° S), but has a clear maximum surrounding Sao Paulo and Rio de Janeiro (> 25%) with poorer performance outside this region (< 10%). This Southeast Brazil maximum captures the initial deployment of the Earth Networks upgrade to BrazilDat lightning detection network [25]. These GBNs are continuously upgraded, and this analysis describes only one year of observations (2012), so caution must be taken when interpreting these results. Regardless, these distributions illustrate the importance of investigating regional averages alongside spatial flash density plots.

Both the regional averages (Table 2) and spatial plots (Fig. 2) can disguise temporal variability. Figure 3 illustrates the daily DE of each network relative to LIS for (a) the entire Western Hemisphere domain and (b) North America (includes land masses in Central America and the Caribbean). In the Western Hemisphere, the daily DE for WWLLN (GLD360/ENTLN) generally exceeds 5-10% (20%), and both GLD360 and ENTLN often detect more than 30% of LIS flashes during April through September (i.e., summer in North America). The North America distributions (panel b) show some interesting patterns. Although only 2012 is examined, seasonal variability is evident (especially for WWLLN), with greater relative DE values during the cold season. This seasonal variability suggests that meteorological conditions contribute to these distributions. For North America, the daily DE for ENTLN (GLD360) typically exceeds 50% (30%). The

rather large day-to-day variations result from the limited sampling provided by LIS. If LIS only observes flashes where these networks are less sensitive, then the daily DE values will be reduced. These distributions are greatly affected by both meteorology and technology, so it is important to continually evaluate and understand the GBN performance.

Despite the variability shown herein, these distributions suggest that each network provides the coverage necessary for many National Weather Service (NWS) Outside the Contiguous United States (OCONUS) operations. Data from each of these networks shows promise for many meteorological applications on many different scales. Within CONUS, NWS forecasters are expanding upon the successful National Lightning Detection Network (NLDN) legacy by including ENTLN observations. Outside CONUS, the WWLLN data have been used for several years to observe convective weather patterns [e.g., 26, 27, 28], and more recently to monitor for volcanic eruptions [29]. Weather forecasters also have begun including GLD360 observations in their operations, with the Ocean Prediction Center (OPC) implementing GLD360 density grids in their analysis software. The OPC forecasters are now able to continually monitor the convective mode (e.g., supercell) and its evolution, rather than waiting for individual microwave overpasses to observe beneath cold cloud shields. Our results provide valuable information on the performance of ground-based lightning observations, which will help improve forecaster confidence in the lightning information.

IV. SUMMARY

This study evaluated data from the World Wide Lightning Location Network (WWLLN), Earth Networks Total Lightning Network (ENTLN), and Global Lightning Dataset 360 (GLD360) relative to the Tropical Rainfall Measurement Mission (TRMM) Lightning Imaging Sensor (LIS). The study domain is the LIS field of view (38° N and 38° S) in the Western Hemisphere (0° to -180° W). We determined the fraction of LIS flashes that were detected by the ground-based networks (GBNs) to improve our understanding of GBN detection capabilities and enhance use of these data in weather research and operations. The results provide valuable information on the relationship between ground- and satellite-based lightning observations, which will become increasingly important as launch of the GOES-R Geostationary Lightning Mapper (GLM) approaches. The GLM will provide data at spatial and temporal scales that are currently unavailable, so these existing networks must be used to simulate future capabilities.

During 2012 in our domain, WWLLN observed ~110 million strokes, ENTLN detected ~413 million strokes, and GLD360 reported ~285 million strokes (in a smaller domain). Lightning density maps resembled previously published lightning climatologies. The GBNs had greatest densities in North and Central America, whereas LIS had greatest densities in Central and South America. The LIS observed 646,999 flashes (520,720 in the GLD360 domain), and the WWLLN, ENTLN, and GLD360 detected 59 242 (9.2%), 181 044 (28.0%), and 131 742 (25.3%) of those flashes, respectively.

We described both the spatial and temporal variability of the GBN performance, and showed greater relative DE over North America, with the exception of the WWLLN. That network exhibited a clear contrast in DE between the continental and oceanic regions. WWLLN detected 17.3% of all LIS flashes over the oceans, with most oceanic grid cells having relative DE values above 15%. The ENTLN and GLD360 had large regions of relative DE greater than 25%, with no clear contrast between land and ocean.

Our analysis revealed that the average regional values can hide important spatial variability, and that both the regional averages and spatial plots can disguise temporal variability. Although only one year was examined, seasonal variability was evident (especially for WWLLN), with greater relative DE values during the cold season. In the Western Hemisphere, the daily DE for WWLLN (GLD360/ENTLN) generally exceeded 5-10% (20%). For North America, the daily DE for ENTLN (GLD360) typically exceeded 50% (30%). Rather large day-to-day variations were observed, likely due in part to the limited sampling provided by LIS. The variability in these distributions illustrates the importance of investigating regional averages alongside spatial flash density plots.

Each of the GBNs have strengths and weaknesses in terms of detection efficiency and location accuracy, types of lightning detected, and areal coverage, but this paper did not attempt to quantify or explain any differences between these networks. These networks are continuously upgraded, and this analysis described only one year of observations (2012), so caution must be taken when interpreting these results. Despite the variability shown herein, each network appears to provide the coverage necessary for many meteorological applications on many different scales. Results provide valuable information on the performance of ground-based lightning observations, which will help lightning vendors better characterize their networks and improve forecaster confidence in the lightning information.

ACKNOWLEDGMENTS

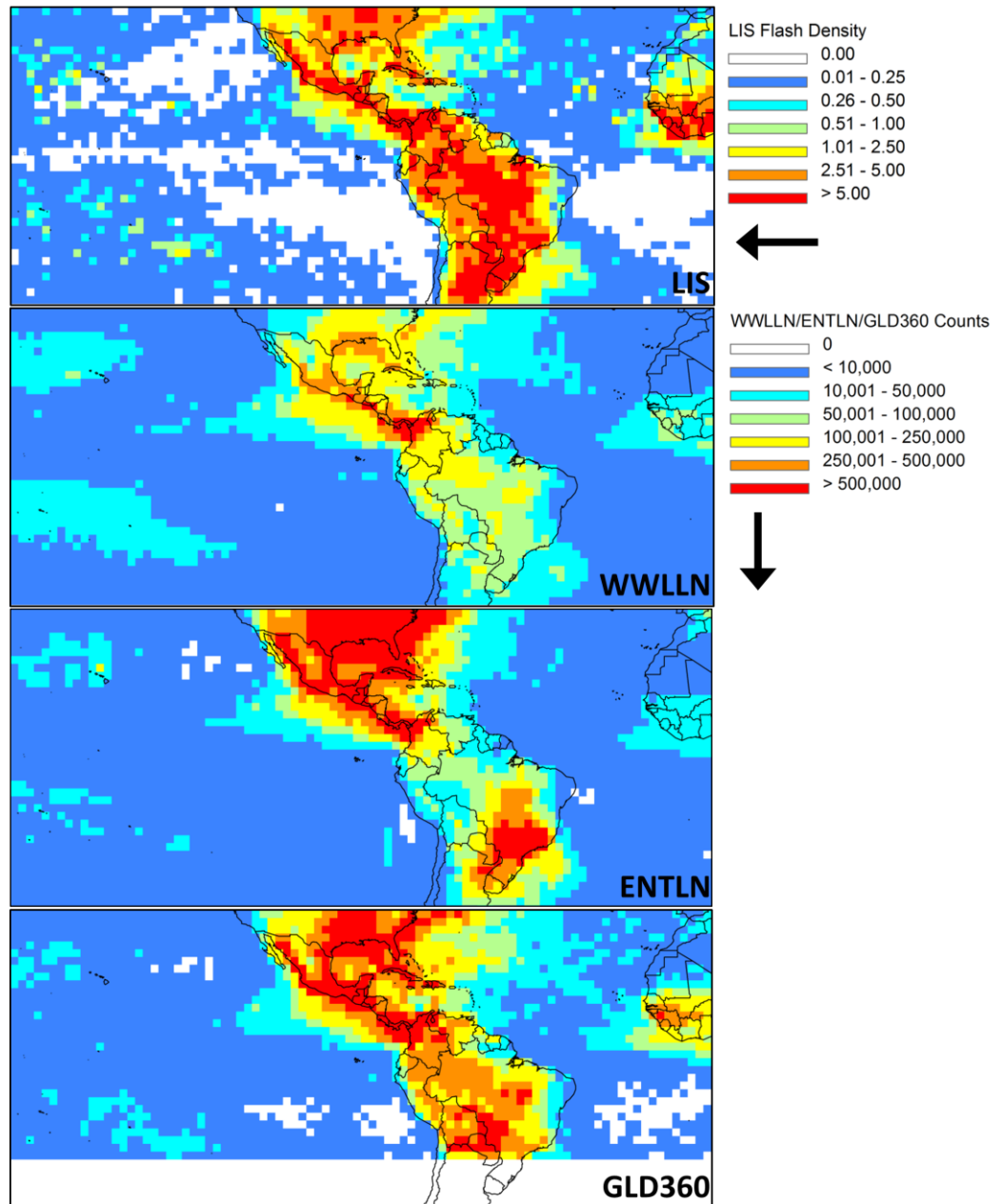
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REFERENCES

- [1] Goodman S. J. and Co-Authors, 2013: The GOES-R Geostationary Lightning Mapper (GLM). *Atmos. Res.*, 125-126, 34-49, doi:10.1016/j.atmosres.2013.01.006.
- [2] Christian, H. J., 1999: The lightning imaging sensor. In NASA CONFERENCE PUBLICATION, 746-749. NASA.
- [3] Boccippio, D. L., W. J. Koshak, and R. J. Blakeslee, 2002: Performance assessment of the optical transient detector and lightning imaging sensor. Part I: Predicted diurnal variability. *J. Atmos. Oceanic Technol.*, 19(9), 1318-1332. doi:10.1175/1520-0426(2002)019<1318:PAOTOT>2.0.CO;2.
- [4] Cecil, D. J., D. E. Buechler, and R. J. Blakeslee, 2014: Gridded lightning climatology from TRMM-LIS and OTD: Dataset description. *Atmos. Res.*, 135-136, 404-414, doi:10.1016/j.atmosres.2012.06.028.
- [5] Christian, H. J., R. J. Blakeslee, and S. J. Goodman, 1992: Lightning Imaging Sensor (LIS) for the Earth Observing System. NASA TM-4350, 44 pp. [Available from Center for Aerospace Information, P.O. Box 8757, Baltimore-Washington International Airport, Baltimore, MD 21240.].
- [6] Simpson, J., C. Kummerow, W. K. Tao, and R. F. Adler, 1996: On the Tropical Rainfall Measuring Mission (TRMM). *Meteorology and Atmospheric Physics*, 60(1), 19-36.
- [7] Christian, H. J., and Co-authors, 2003: Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. *J. Geophys. Res.*, 108(D1), 4005. doi: 10.1029/2002JD002347
- [8] 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.
- [9] 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, doi:10.5194/angeo-22-747-2004.
- [10] 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.
- [11] Hutchins, M. L., R. H. Holzworth, K. S. Virts, J. M. Wallace and S. Heckman, 2013: Radiated VLF energy differences of land and oceanic lightning. *Geophys. Res. Lett.*, 40(10), 2390-2394, doi: 10.1002/grl.50406.
- [12] Crombie, D. D., 1964: Periodic fading of VLF signals received over long paths during sunrise and sunset. *J. Res. Bur. Stand., Radio Sci.*, 68D, 27-34.
- [13] 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.
- [14] Rodger, C. J., J. B. Brundell, R. H. Holzworth, and E. H. Lay, 2009: Growing detection efficiency of the World Wide Lightning Location Network. *AIP Conf. Proc.*, 1118, 15-20. doi:10.1063/1.3137706.
- [15] 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.
- [16] Liu and Heckman 2012 Liu, C., and S. Heckman, 2012: Total lightning data and real-time severe storm prediction. *Conf. Meteorological Environmental Instruments and Methods of Observation Management Group*, 10th Session, Brussels, Belgium, World Meteorological Organization, 16-18 October 2012 - P5 (10)
- [17] Said, R. K., U. S. Inan, and K. L. Cummins, 2010: Long-range lightning geolocation using a VLF radio atmospheric waveform blank. *J. Geophys. Res.*, 115, D23108.
- [18] Pierce, E.T., 1977: Atmospherics and radio noise. In: Golde, R.H. (Ed.), *Lightning 1: Physics of Lightning*, pp. 351-384.
- [19] Said, R. K., M. B. Cohen, and U. S. Inan, 2013: Peak currents and incidence of land and oceanic lightning: Global observations by the GLD360 network. *J. Geophys. Res.*, 118, 6905-6915, doi:10.1002/jgrd.50508, 2013
- [20] Biswas, K. R. and P. V. Hobbs, 1990: Lightning over the gulf stream. *Geophys. Res. Lett.*, 17(7), 941-943. doi:10.1029/GL017i007p00941.
- [21] 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. Wea. Rev.*, 129, 1179-1193, doi: 10.1175/1520-0493(2001)129<1179:CTGLIT>2.0.CO;2.

- [22] Rudlosky, S. D., and H. E. Fuelberg, 2010: Pre- and postupgrade distributions of NLDN reported cloud-to-ground lightning characteristics in the contiguous United States. *Mon. Wea. Rev.*, 138, 3623–3633, doi:10.1175/2010MWR3283.1.
- [23] Orville, R. E., G. R. Huffines, W. R. Burrows, and K. Cummins, 2011: The North American Lightning Detection Network (NALDN): Analysis of flash data – 2001–2009. *Mon. Weather Rev.*, 139, 1305–1322, doi:10.1175/2010MWR3452.1
- [24] Jacobson, A. R., R. H. Holzworth, J. Harlin, R. L. Dowden, and E. H. Lay, 2006: Performance assessment of the World Wide Lightning Location Network (WWLLN), using the Los Alamos Sferic Array (LASA) as ground truth. *J. Atmos. Oceanic Technol.*, 23, 1082–1092.
- [25] Naccarato, K. P., O. Pinto Jr., and G. Zepka, 2013: Severe storms tracking and nowcasting in Southeastern Brazil based on numeric prediction models and total lightning data from BRASILDAT network. *6th Conf. Meteorol. App. Lightning Data*, Amer. Meteor. Soc., Austin, TX, January 7–10, Paper 2.4.
- [26] Lay E. H., A. R. Jacobson, R. H. Holzworth, C. J. Rodger, and R. L. Dowden, 2007: Local time variation in land/ocean lightning count rates as measured by the World Wide Lightning Location Network. *J. Geophys. Res.*, 112, D13111, doi:10.1029/2006JD007944.
- [27] 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.
- [28] Abarca, S. F., K. L. Corbosiero, 2011: The World Wide Lightning Location Network and convective activity in tropical cyclones. *Mon. Wea. Rev.*, 139, 175–191.
- [29] Ewert, J. W., R. H. Holzworth, and A. K. Diefenbach, 2009: Detecting explosive volcanic eruptions with the World Wide Lightning Location Network (WWLLN). *American Geophysical Union*, Fall Meeting, San Francisco, CA, December.

Fig. 1. Top to bottom, LIS flash density, WWLLN stroke count, ENTLN stroke count, and GLD360 stroke count during 2012. Each map shows similar spatial patterns and resembles the many previously published lightning climatologies.



Network Detection Efficiency Relative to TRMM/LIS (2012)

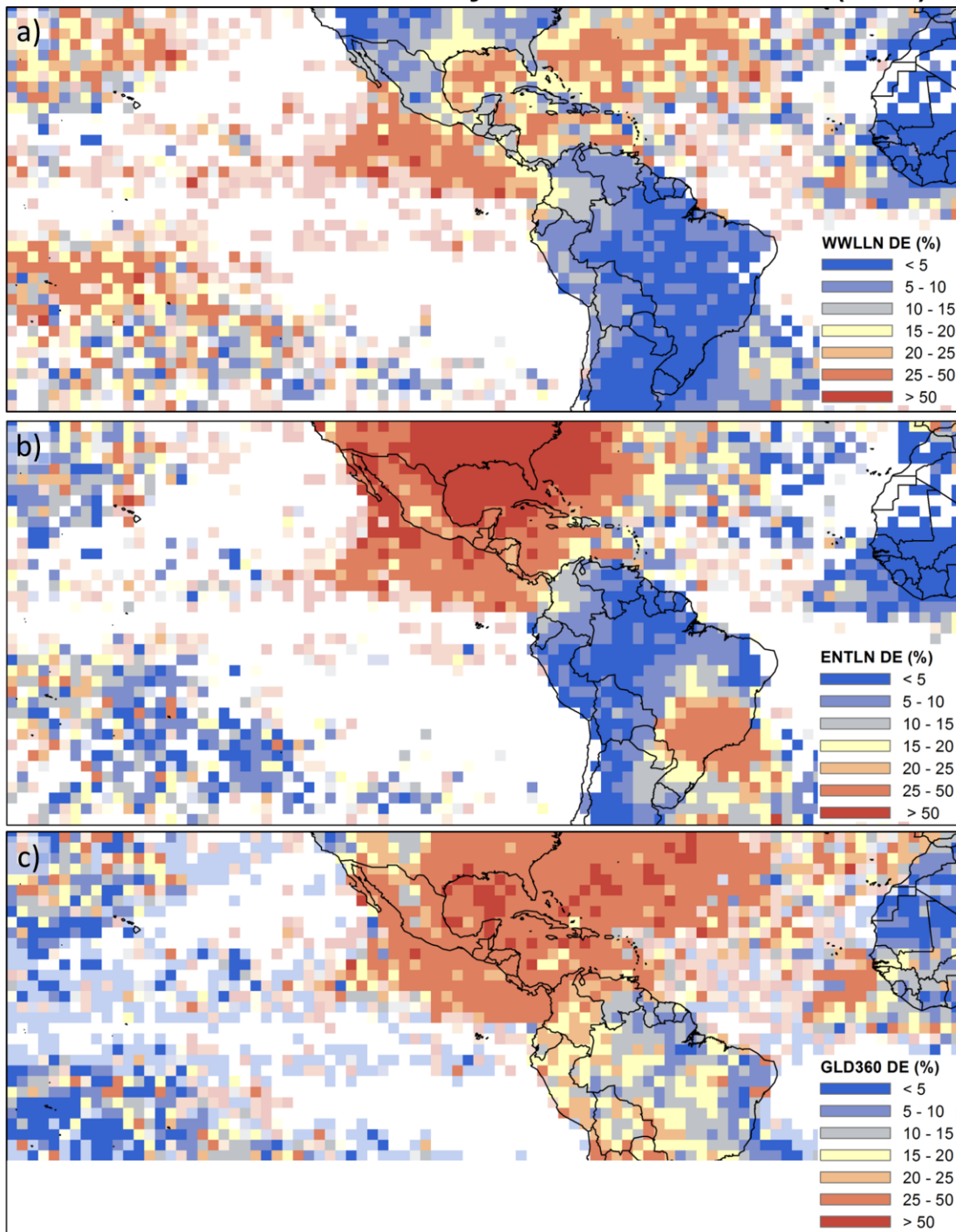


Fig. 2. Maps of relative DE computed by dividing the sum of the “matched” LIS flashes (i.e., those seen by the GBN) by the sum of “all” LIS flashes within $2^\circ \times 2^\circ$ grid cells. Panel (a) shows WLLN, b) ENTLN, and c) GLD360. Note that white grid cells indicate no LIS flashes, and that grid cells with less than 15 LIS flashes are reduced in brightness to illustrate the reduced confidence in DE estimates from those areas (i.e., exclusively over the oceans).

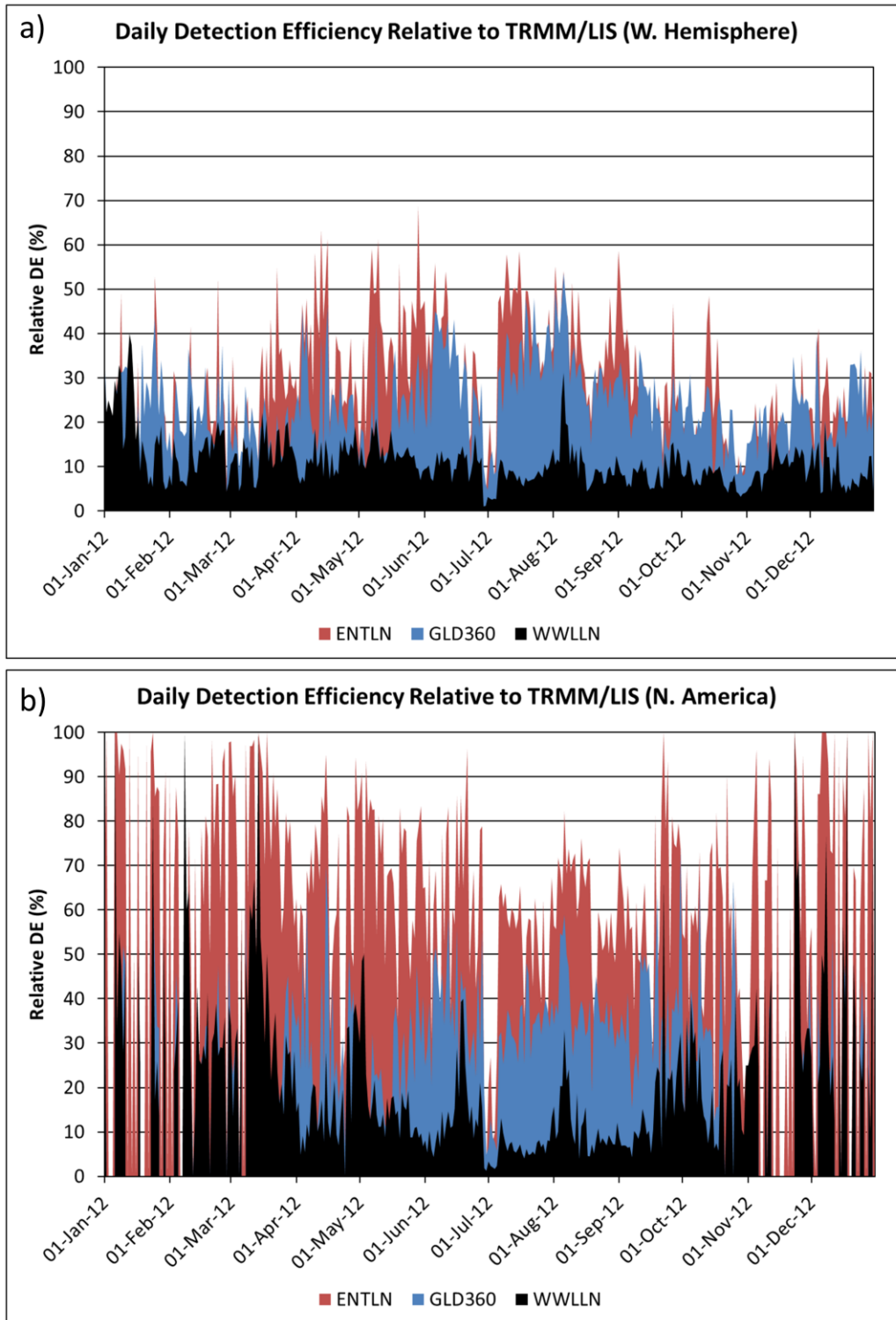


Fig. 3. The daily DE of each network relative to the LIS for (a) the entire Western Hemisphere domain and (b) North America (includes land masses in Central America and the Caribbean). Note that no red in panel (a) indicates that the GLD360 DE was the same or higher than the ENTLN DE, and no blue in panel (b) indicates that the WWLLN DE was the same or higher than the GLD360 DE.