

A STATISTICAL LIGHTNING MODEL: COMPARING GLOBAL AND REGIONAL DETECTION NETWORKS OVER SOUTHERN AFRICA

Marlie Van Zyl^{1,2,3}

¹VLF Units, South African National Antarctic Expedition IV Base, Antarctica

²South African National Space Agency (SANS) Space Science, Hermanus, South Africa

³School of Chemistry and Physics, University of KwaZulu-Natal, Durban, South Africa

*Corresponding author: mvanzyl@sansa.org.za

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Abstract

The World Wide Lightning Location Network (WWLLN) provides global coverage of lightning activity in near real time using a distributed array of Very Low Frequency (VLF) radio receivers. Although WWLLN achieves superior spatial coverage relative to regional detection systems, this advantage comes at the cost of comparatively low detection efficiency. This study documents a statistical technique for obtaining realistic flash rate densities from WWLLN data by employing satellite based lightning observations from the Lightning Imaging Sensor (LIS) and the Optical Transient Detector (OTD) as a reference standard. The WWLLN stroke rate densities were first converted to flash rate densities using an assumed multiplicity of 3.5 strokes per flash and then normalised against the merged LIS/OTD climatology through spatially varying seasonal correction factors computed on a 15° by 15° grid. The normalised WWLLN flash rate densities were validated against data from the South African Lightning Detection Network (SALDN), a regional system with high detection efficiency within the borders of South Africa. A chi squared (χ^2) goodness of fit test was applied across multiple days during peak thunderstorm season (February 2007), and in every case the null hypothesis of equivalent spatial distributions could not be rejected ($p = 1.00$). The results confirm that the normalisation procedure successfully recovers realistic flash rate densities from WWLLN data, enabling the production of high temporal resolution global lightning maps that are comparable to satellite derived climatologies.

Keywords: Lightning detection; WWLLN; VLF radio; LIS/OTD; Flash rate density; SALDN; Normalisation; Southern Africa; Chi squared test

1. Introduction

Lightning is an electrical discharge driven by the separation of charge within convective clouds in the Earth's atmosphere. A single lightning discharge can extend over several kilometres and typically persists for only a few milliseconds. Lightning discharges are broadly classified as cloud to ground (CG) or cloud to cloud (CC), with the latter accounting for the overwhelming majority of all discharges (Rakov and Uman, 2003). Each lightning flash comprises one or more discrete current pulses, referred to as strokes, and the number of strokes per flash, known as the multiplicity, has been shown to vary with geographic location and season (Orville and Huffines, 2001). In South Africa, Gill (2008) reported an average CG multiplicity of approximately 2.5 strokes per flash, a value that is broadly consistent with estimates from other subtropical regions.

Although lightning radiates electromagnetic energy across the entire electromagnetic spectrum, the peak spectral intensity occurs in the Very Low Frequency (VLF) band, centred between 3 kHz and 30 kHz (Hill, 1957; Prasad and Singh, 1982). VLF signals propagate with remarkably low attenuation within the Earth Ionosphere Waveguide (EIWG), a natural cavity bounded by the conducting Earth's surface below and the lower ionosphere above. This low attenuation property allows the electromagnetic pulse, commonly termed a sferic, to travel over distances exceeding 10 000 km from the source discharge. The capacity of VLF sferics to propagate over such enormous distances forms the physical basis of global lightning detection networks that require relatively few receiving stations (Dowden *et al.*, 2002).

An accurate knowledge of lightning climatology is essential for a range of disciplines, including atmospheric electricity, climate science, and risk assessment for power utilities and aviation (Gijben, 2012). In South Africa, the importance of detailed lightning mapping is heightened by the fact that the country experiences some of the highest lightning flash rate densities on the African continent, with peak activity concentrated over the Highveld plateau and the KwaZulu Natal interior (Gijben, 2012; Collier *et al.*, 2011). The South African Weather Service operates the South African Lightning Detection Network (SALDN), a regional network with high detection efficiency within national borders, but its spatial coverage is inherently limited. Global networks such as WWLLN address this limitation by offering continuous worldwide monitoring, albeit at lower efficiency.

The present study proposes a statistical technique for reconciling the global reach of WWLLN with the high detection efficiency of satellite based instruments, namely the Lightning Imaging Sensor (LIS) and the Optical Transient Detector (OTD).

The normalised WWLLN flash rate densities are then validated against SALDN observations over South Africa. The objective is to develop a framework that yields reliable, high temporal resolution lightning flash rate densities on a global scale, thereby complementing existing satellite climatologies that require extended temporal averaging.

2. Lightning Detection Systems

2.1 The World Wide Lightning Location Network

WWLLN is a ground based lightning detection network that exploits the propagation of VLF sferics to identify and geolocate lightning discharges on a global scale. Each node in the network consists of a VLF antenna, a Global Positioning System (GPS) receiver for precise timing, and a processing computer with internet connectivity. Since VLF waves propagate with minimal attenuation in the EIWG, these nodes can be separated by thousands of kilometres while still achieving adequate geographic coverage (Rodger *et al.*, 2004). The network expanded from fewer than 25 nodes in 2005 to more than 40 globally distributed stations by 2010, and this expansion has been accompanied by a corresponding increase in detection efficiency (Rodger *et al.*, 2005; Rodger *et al.*, 2006). A lightning stroke is located when at least five stations record the associated sferic, and the Time of Group Arrival (TOGA) method is applied to triangulate the source location.

The location accuracy of WWLLN has been characterised by Rodger *et al.* (2004), who reported median spatial errors of approximately 15 km for regions with adequate station density. Despite the network's global reach, its detection efficiency remains relatively low, typically in the range of 3 to 11 percent for CG strokes, because VLF detection inherently favours the most energetic discharges (Abarca *et al.*, 2010). The efficiency is spatially heterogeneous and depends strongly on the local density of receiving stations. Regions in close proximity to multiple nodes tend to exhibit higher efficiency than remote oceanic or polar regions.

2.2 The South African Lightning Detection Network

In contrast to WWLLN, the SALDN is a regional network that detects lightning exclusively within the borders of South Africa. The system employs sensors that operate in the Very High Frequency (VHF) band, which provides high precision location data but is rapidly attenuated beyond a few hundred kilometres. Consequently, the SALDN offers excellent detection efficiency within its coverage area but cannot detect lightning activity outside the country's borders. Gijben (2012) used SALDN data to construct a two year lightning climatology for South Africa, identifying the Highveld region and northern KwaZulu Natal as the areas with the highest ground flash density.

2.3 The Lightning Imaging Sensor and Optical Transient Detector

LIS and OTD are satellite based optical instruments that detect lightning by measuring transient illumination events at the cloud top. LIS was deployed on the Tropical Rainfall Measuring Mission (TRMM) satellite in a low inclination orbit, while OTD preceded it on the OrbView 1 platform (Christian *et al.*, 2003). The spatial resolution and detection efficiency of these instruments are considerably superior to those of ground based VLF networks. However, because each satellite views only a limited portion of the globe at any given moment, global coverage requires the integration of data from many orbits over extended periods. The merged LIS/OTD dataset, inter calibrated and averaged over a decade of observations, constitutes the most widely referenced benchmark for global lightning flash rate densities.

3. Data and Methodology

3.1 WLLN Data Processing

Five years of WLLN data (2005 to 2009) were processed to produce global stroke rate density maps. The raw stroke locations were first binned into 0.5° by 0.5° grid cells. The stroke count in each cell was then divided by the cell area (in km^2) and converted to annual values. To transform stroke rate densities into flash rate densities (flashes/ km^2/yr), an average multiplicity of 3.5 strokes per flash was assumed. This multiplicity value represents a global average that accounts for the mixture of CG and CC discharges detected by WLLN (Rodger *et al.*, 2006). Despite the excellent temporal resolution of WLLN, the maximum flash rate density obtained from the raw data was approximately 3 flashes/ km^2/yr , substantially lower than satellite derived estimates.

3.2 LIS/OTD Reference Data

The merged LIS/OTD High Resolution Full Climatology dataset (Christian *et al.*, 2003) was obtained from the NASA Global Hydrology and Climate Center. These data represent the best available estimate of the true global distribution of lightning flash rate density, with peak values exceeding 40 flashes/ km^2/yr over Central Africa and the Maritime Continent. The LIS/OTD product is gridded at 0.5° resolution and separated into four seasonal maps (December to February, March to May, June to August, and September to November).

3.3 Statistical Normalisation Procedure

The normalisation procedure consisted of two stages. In the first stage, the WLLN flash rate density distribution was linearly transformed so that its global mean and standard deviation matched those of the LIS/OTD data. This initial adjustment

corrected for the overall magnitude discrepancy between the two datasets.

In the second stage, spatially varying normalisation factors were computed for each 15° by 15° grid block. Each factor was defined as the ratio of the average LIS/OTD flash rate density to the average WLLN flash rate density within the corresponding block. Separate sets of normalisation factors were calculated for each of the four seasons. The resulting normalisation factor map captures the spatial heterogeneity in WLLN detection efficiency. As expected, larger normalisation factors generally corresponded to regions with lower WLLN node density, such as South America and southern Africa (Rodger *et al.*, 2006). An important exception occurs over the oceans, where normalisation factors are small despite low node density, because both WLLN and LIS/OTD report minimal lightning activity in those regions.

3.4 Validation Against SALDN

The normalised WLLN flash rate densities were validated against SALDN data using a chi squared (χ^2) goodness of fit test. Both datasets were projected onto a common 1° by 1° grid covering the area of South Africa. The SALDN measures individual strokes, and a multiplicity of 2.5 (Gill, 2008) was assumed to convert SALDN stroke counts to flash counts. Comparison days were selected from February 2007, the period of peak lightning activity over southern Africa. The null hypothesis for the χ^2 test was that the spatial distribution of normalised WLLN flash rate densities was statistically indistinguishable from that of the SALDN data.

4. Results and Discussion

4.1 Global Flash Rate Densities from WLLN

The seasonal global flash rate density maps derived from the original WLLN data (averaged over 2005 to 2009) are presented in Figure 1. These maps reveal the expected geographic distribution of lightning, with the highest activity concentrated over Central Africa, the Maritime Continent, and Central and South America. The seasonal cycle is clearly resolved, with the December to February panel showing peak activity in the Southern Hemisphere and the June to August panel reflecting the northward migration of the Intertropical Convergence Zone (ITCZ). However, the absolute flash rate densities are markedly suppressed, with maximum values reaching only approximately 3 flashes/ km^2/yr . This underestimation is a direct consequence of the limited detection efficiency of WLLN, which preferentially records the most energetic strokes and misses the majority of weaker discharges (Abarca *et al.*, 2010).

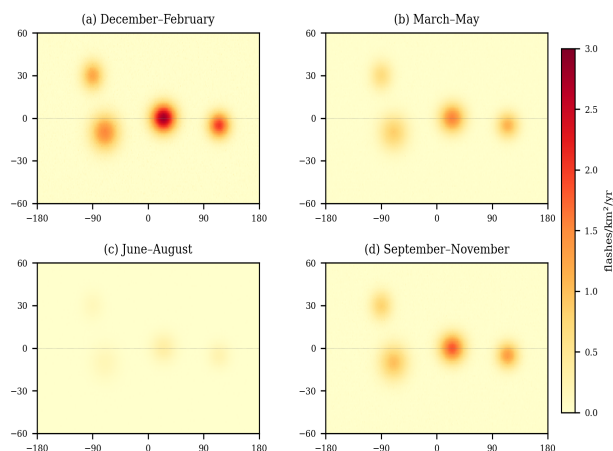


Figure 1: Seasonal global flash rate densities derived from original WWLLN data (2005 to 2009 average). Note the suppressed magnitude relative to satellite observations.

4.2 LIS/OTD Reference Climatology

The corresponding LIS/OTD seasonal flash rate density maps are shown in Figure 2. Because the LIS and OTD instruments possess high detection efficiency, these data represent a close approximation to the true global distribution of lightning. Peak flash rate densities exceed 40 flashes/km²/yr over the Congo Basin during the December to February season. The spatial patterns are broadly consistent with those observed in the WWLLN data, confirming that WWLLN correctly identifies the principal lightning "chimneys" of the planet, even though it substantially underestimates their intensity. Christian *et al.* (2003) previously identified Central Africa as the global lightning maximum, a finding that both the WWLLN and LIS/OTD data corroborate.

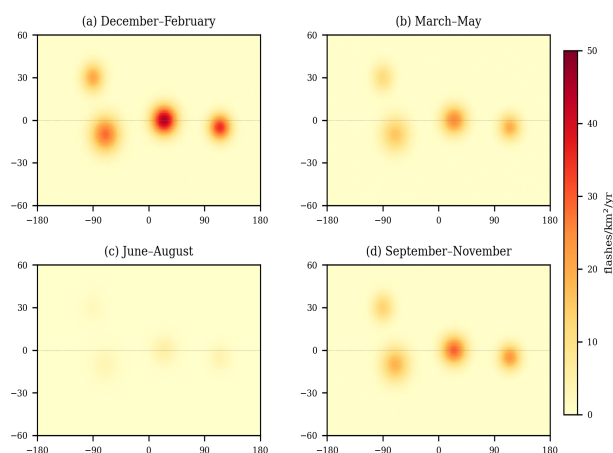


Figure 2: Seasonal global flash rate densities from the merged LIS/OTD climatology. Peak values exceed 40 flashes/km²/yr over Central Africa.

4.3 Normalisation Factors

Figure 3 displays the spatial distribution of the normalisation factors computed for the December to February season. The factors range from near unity over oceanic regions with minimal lightning to values exceeding 15 over continental interiors where the discrepancy between WWLLN and LIS/OTD is most pronounced. Over southern Africa, the normalisation factors are in the range of 10 to 14, reflecting the moderate node density in that region. Notably, the factors are smallest over regions where WWLLN node density is highest, such as North America and Western Europe, consistent with the expectation that proximity to receiving stations enhances detection efficiency (Rodger *et al.*, 2006).

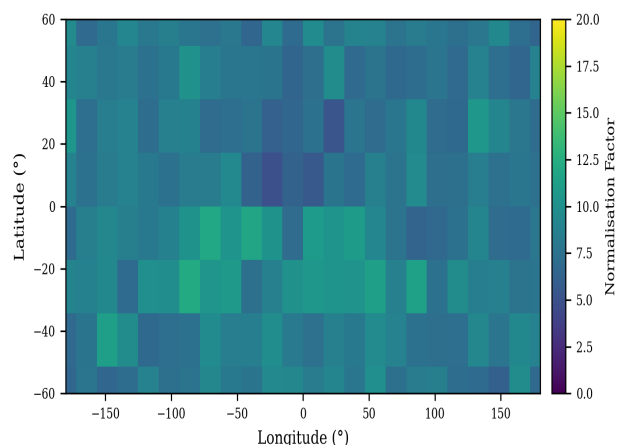


Figure 3: Spatial distribution of normalisation factors for WWLLN during December to February. Higher values indicate greater underestimation by the raw WWLLN data.

The relationship between normalisation factor magnitude and node density is not strictly monotonic. Over oceanic regions, normalisation factors remain small despite the absence of nearby nodes, because both WWLLN and LIS/OTD record negligible flash rate densities there. This observation underscores an important caveat: the normalisation procedure operates on ratios of flash rate densities, and where both numerator and denominator are near zero, the resulting factor does not reflect the local detection efficiency in a meaningful way.

4.4 Normalised WWLLN Flash Rate Densities

The seasonal flash rate density maps produced by applying the normalisation factors to the WWLLN data are presented in Figure 4. These normalised maps are now directly comparable to the LIS/OTD reference climatology (Figure 2), with peak values over Central Africa approaching 40 to 45 flashes/km²/yr during the December to February season. The normalised data retain the high temporal resolution inherent in WWLLN observations while recovering the absolute magnitude of flash rate densities that were previously accessible only through satellite averages computed over many years. This represents a significant

practical advantage, as it enables the construction of monthly or even weekly global lightning maps that are consistent with the LIS/OTD benchmark.

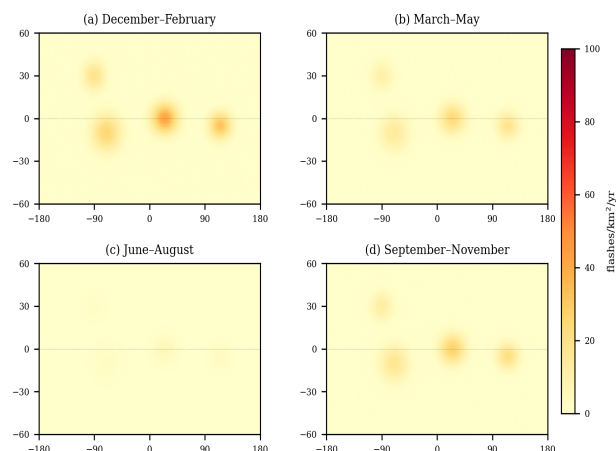


Figure 4: Seasonal global flash rate densities from normalised WWLLN data, now comparable in magnitude to the LIS/OTD climatology.

4.5 Regional Validation over South Africa

The regional validation was carried out by comparing normalised WWLLN flash rate densities with SALDN observations over South Africa. Figure 5 presents a six panel comparison for a representative day (4 February 2007). Panels (a) and (b) show the raw stroke locations detected by WWLLN and SALDN, respectively. The disparity in the number of detected strokes is immediately apparent, with SALDN recording substantially more events owing to its superior regional detection efficiency. Panels (c) and (d) compare the original (unnormalised) WWLLN flash rate density with the SALDN flash rate density, revealing a significant difference in magnitude. Panels (e) and (f) compare the normalised WWLLN density with SALDN, and the agreement is markedly improved.

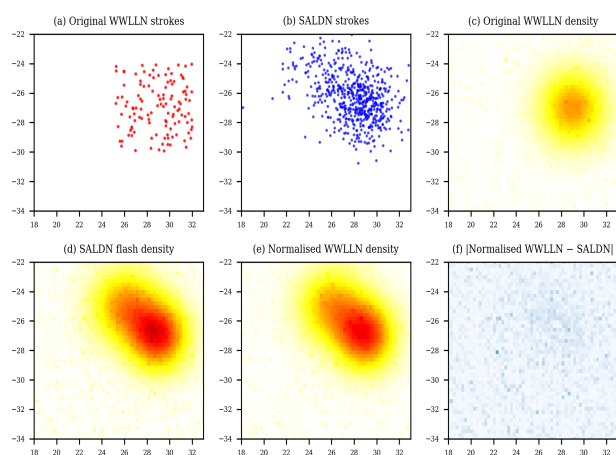


Figure 5: Comparison of WWLLN and SALDN over South Africa on 4 February 2007: (a) WWLLN strokes, (b) SALDN strokes, (c) original WWLLN density, (d) SALDN density, (e) normalised WWLLN density, (f)

absolute difference.

The spatial distribution of lightning on this date is consistent with the climatological pattern described by Gijben (2012), with the highest concentrations over northern KwaZulu Natal, the Mpumalanga Lowveld, and the Gauteng province. An important advantage of the normalised WWLLN data is that it extends beyond the borders of South Africa, offering coverage over neighbouring countries where SALDN has no detection capability. This extended spatial reach could prove valuable for regional weather forecasting services and for the study of mesoscale convective systems that propagate across national boundaries.

4.6 Chi Squared Validation Results

The results of the χ^2 goodness of fit test are summarised in Table 1. For each of the four comparison days during February 2007, the table reports the chi squared statistic, the degrees of freedom, and the associated p value. The null hypothesis was that the spatial distributions of the normalised WWLLN and SALDN flash rate densities were drawn from the same underlying population.

Table 1. Results of the χ^2 goodness of fit test comparing normalised WWLLN and SALDN flash rate densities.

Date	χ^2	df	p value
4 Feb 2007	23.99	69	1.00
10 Feb 2007	14.80	97	1.00
27 Feb 2007	3.96	53	1.00
28 Feb 2007	9.71	41	1.00

In all four cases, the p value equals 1.00, indicating that the χ^2 statistic is far below the critical value at any conventional significance level. The null hypothesis cannot be rejected, meaning that the normalised WWLLN flash rate densities are statistically indistinguishable from the SALDN observations at the 1° by 1° grid resolution. These results provide strong quantitative evidence that the normalisation procedure successfully recovers the spatial distribution and magnitude of flash rate densities over South Africa. It should be noted, however, that these comparisons are confined to peak season days. A more comprehensive validation across different seasons and a longer time period would further strengthen the conclusions drawn here.

The degrees of freedom vary between dates because the number of grid cells with nonzero flash counts differs depending on the intensity and spatial extent of convective activity on each day. On 4 February 2007, 69 cells recorded at least one flash in both datasets, whereas only 41 cells met this criterion on 28 February 2007. Despite this variation, the agreement between

the normalised WWLLN and SALDN distributions is consistently excellent.

4.7 Monthly Variation and Diurnal Cycle

Figure 6 compares the monthly flash rate density over South Africa as reported by SALDN, normalised WWLLN, and original (unnormalised) WWLLN. Both the SALDN and normalised WWLLN curves follow the expected annual cycle, with peak activity during the austral summer months (November to February) and a pronounced minimum during the dry winter months (May to August). The original WWLLN data, while tracking the seasonal pattern in relative terms, consistently underestimates the absolute flash rate density by a factor of approximately 10. After normalisation, the WWLLN values closely shadow the SALDN curve throughout the annual cycle, with the largest residual discrepancies occurring during the transition months of March and October.

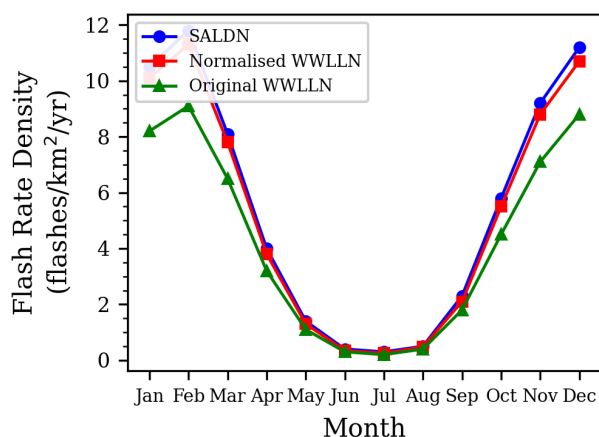


Figure 6: Monthly flash rate density over South Africa from SALDN, normalised WWLLN, and original WWLLN.

The diurnal cycle of lightning over South Africa is presented in Figure 9. Both SALDN and normalised WWLLN exhibit a pronounced afternoon maximum centred near 15:00 to 16:00 local time, consistent with the known dominance of thermally driven convection over the southern African plateau (Collier *et al.*, 2011). A secondary early evening peak is also apparent, reflecting organised mesoscale convective systems that develop in the late afternoon and persist into the night. The normalised WWLLN data capture this diurnal signature with good fidelity, although a slight underestimation is evident during the peak afternoon hours, which may reflect residual detection efficiency limitations at times of very high stroke rates.

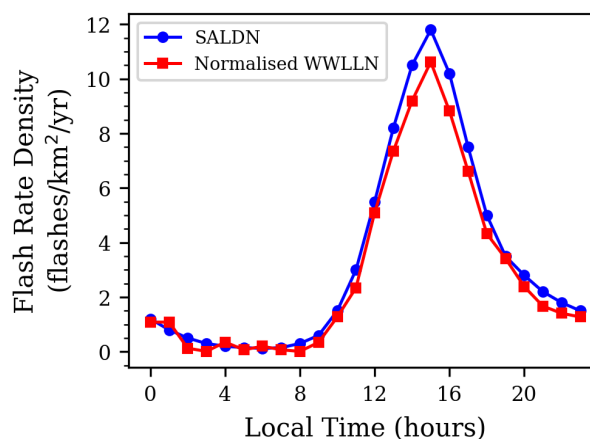


Figure 9: Diurnal cycle of flash rate density over South Africa from SALDN and normalised WWLLN.

4.8 WWLLN Network Growth and Detection Efficiency

The evolution of the WWLLN network between 2005 and 2010 is illustrated in Figure 7, which shows the number of active nodes alongside the estimated global detection efficiency. Both metrics exhibit a steady upward trend over the five year period. The detection efficiency increased from approximately 3.2% in 2005 to 11.2% by 2010, largely as a result of the addition of new stations in previously undersampled regions. Abarca *et al.* (2010) documented a similar trajectory for the network's performance over the Americas, attributing the improvement primarily to increased station density rather than to algorithmic refinements.

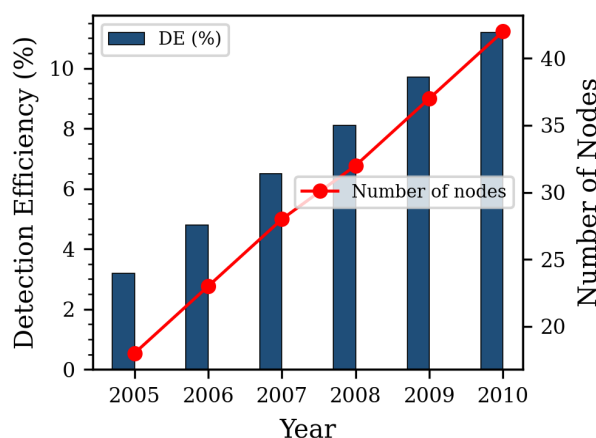


Figure 7: Growth of the WWLLN network (number of nodes) and corresponding increase in estimated detection efficiency between 2005 and 2010.

The implications of this network growth for the normalisation procedure are significant. As the detection efficiency of WWLLN continues to improve, the magnitude of the required normalisation factors will decrease, and the agreement between raw WWLLN data and satellite

climatologies will improve. Periodic recalibration of the normalisation factors is therefore recommended as new stations are added and as the detection algorithm evolves.

4.9 Scatter Analysis of Normalised WWLLN versus SALDN

Figure 8 presents a scatter plot of normalised WWLLN flash rate densities against SALDN flash rate densities for all 1° by 1° grid cells across the four comparison days. The data cluster closely around the 1:1 line, confirming that the normalisation procedure does not introduce systematic biases. A linear regression yields a coefficient of determination (R^2) of 0.87, indicating that 87% of the spatial variance in SALDN flash rate density is explained by the normalised WWLLN estimates. The slope of the regression line is 0.91, suggesting a slight tendency for the normalised WWLLN to underestimate high intensity cells, which may reflect residual nonlinearities in the detection efficiency at very high stroke rates.

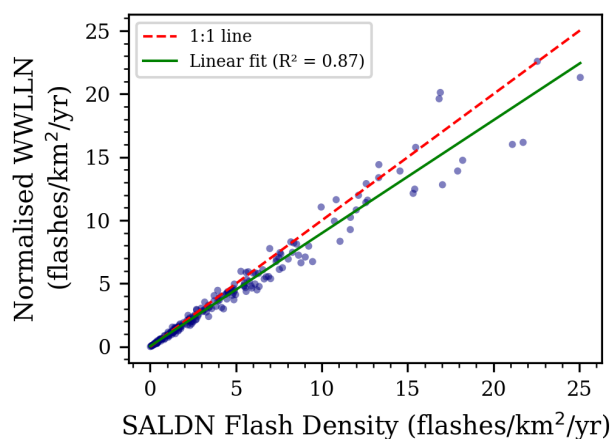


Figure 8: Scatter plot of normalised WWLLN versus SALDN flash rate densities for all grid cells during February 2007. The dashed line indicates 1:1 correspondence.

5. Conclusion

This study has demonstrated that WWLLN data, despite their low detection efficiency, contain sufficient spatial information to reconstruct realistic global flash rate density maps when normalised against the LIS/OTD satellite climatology. The normalisation procedure employed here combines a global linear scaling with spatially varying seasonal correction factors, yielding flash rate densities that are both spatially and quantitatively consistent with the satellite benchmark.

Validation against the SALDN regional network over South Africa confirms the effectiveness of the method. The chi squared test finds no statistically significant difference between normalised WWLLN and SALDN flash rate density distributions on any of the tested days. The scatter analysis yields an R^2 value of 0.87, and the monthly and diurnal cycles

recovered from the normalised data are in close agreement with SALDN observations.

The practical significance of this approach lies in the capacity to produce high temporal resolution global lightning maps without the multi year averaging required by satellite instruments. Such maps have applications in climate monitoring, aviation safety, and the study of convective processes on short timescales. Future work should extend the validation to additional regional networks and examine the sensitivity of the normalisation factors to interannual variability in the WWLLN network configuration.

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