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Research Article

Estimation of detection efficiency of the world wide lightning location network in the democratic republic of congo basin using lightning imaging sensor (LIS) as reference

Abstract

An estimation of detection efficiency of the World Wide Lightning Location Network (WWLLN) in the Congo Basin has been done by comparison of its data with Lightning Imaging Sensor (LIS) data for the same period from 2005 to 2013. This comparison shows the relative detection efficiency of the WWLLN (DE) in the 2500 km × 2500 km region increases from about 1.70% in the beginning of the period to 5.90% in 2013, and it is in agreement with previous results for other regions of the world. However, the increase of DE is not uniform over the whole region.

Keywords: detection efficiency, lightning imaging sensor, DR congo basin

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Introduction

Space observations have shown that the highest concentrations of lightning on the Earth are mostly on the territory of the Democratic Republic of Congo (DR Congo). The global climatology of lightning activity proposed by Christian et al.[1] and based on data recorded during five years (May 1995-March 2000) by the Optical Transient Detector (OTD) loaded on board the satellite MicroLab-1, highlights the features of the lightning distribution on the globe and shows that the greatest rates of flashes (> 50 fl km^{-2} yr^{-1} and up to 82.7 fl km^{-2} yr^{-1} with a resolution of 0.25° × 0.25°) concern the equatorial region of the Congo Basin.

The Lightning Imaging Sensor (LIS) on board the Tropical Rainfall Measuring Mission (TRMM) satellite has detected lightning flashes for seventeen years (1997-2014). It provided a lightning climatology in a restricted area of the Earth between latitudes 38°S and 38°N. From three years observations (1998-2000), Williams et al.[2] analysed the land-ocean contrast of the lightning activity. As Christian et al.[1] they concluded the maximum lightning activity is located in Central Africa. More recently, Cecil et al.[3] detailed the characteristics of the lightning activity across the world from the combined data of LIS and OTD and confirmed the largest rate of lightning are observed in central Africa. The peak of the annual flash rate was found in the East of the DRC with a value of 160 fl km^{-2} yr^{-1}.

Collier et al.[4] developed a study of lightning activity from LIS data to establish statistical and seasonal distribution of the lightning activity in Southern Africa. As in Christian et al.[1] the highest density of lightning (107 fl km^{-2} yr^{-1}) was found in the Congo Basin.

The World Wide Lightning Location Network (WWLLN) is a global lightning detection network around the Earth. A Management Team, led by Prof Robert Holzworth of the University of Washington, collects these data with the cooperation of the universities and institutes which host the stations of detection. The WWLLN data have been used in various studies in the world as lightning climatology,[5] convective activity in tropical cyclones,[6–8] lightning activity for a thunderstorm producing gigantic jets at la Réunion Island,[9] influence of smoke of fires on thunderstorm activity.[10]

The goal of this paper is, by way of preliminary introductory study of lightning climatology in the Congo Basin, to estimate the detection efficiency of the World Wide Lightning Location Network in the Congo Basin by comparison with LIS taken as reference. The next sections are respectively dedicated on data, methodology, results and discussion and summary.

Data

WWLLN data

Data from WWLLN recorded during nine years (2005 to 2013) have been used in this study. The WWLLN (www.wwlln.net/) is a global lightning detection network around the Earth. The electromagnetic radiations emitted by lightning strokes at very low frequency (VLF) and called sferics are detected by the sensors of the WWLLN. These strokes are then localized by using the time of group arrival technique (TOGA).[11] The stations can be separated by thousands of km because the VLF frequencies can propagate within the Earth-Ionosphere wave guide with very little attenuation. The goal was to have about 60 sensors spaced uniformly about 3000 km apart to cover the whole world and to localize at least 50% of the CG flashes with an average accuracy better than 10 km.[12]

Since its implantation in March 2003, the WWLLN has been improved in terms of number of stations and development of the processing algorithm.[13] In 2014, it had more than 60 sensors spread on the planet (Figure 1). Several authors have estimated the evolution of its detection efficiency for limited world regions and time periods by referring either to satellite data or to data provided from regional, national, or commercial flash detection networks.[5–7,12–16] Noted a large increase of stroke detections with additional sensors from 2003 to 2007: 10.6 million in March-December 2003 with 11 sensors to 28.1 million for the same period in 2007 with 30 sensors.

Furthermore, they noted the improvements in the algorithm used to reconstruct the flashes from the WWLLN detections, increased the detection efficiency of the network by 63%. The WWLLN is capable of detecting both CG and IC lightning strokes with a comparable efficiency as long as their peak currents are comparable.[12,14,15] However, since CG strokes have higher peak currents, the detection efficiency is about twice that of the IC strokes as reported by Bovalo et al.[5] Recent research indicates the detection efficiency of the network is approximately 10% (35%) for strokes with a peak current larger than ±35 kA (-130 kA).[16]

LIS data

LIS is an optical sensor of the scientific payload on the TRMM satellite (http://thunder.msfc.nasa.gov/lis/overview_lis_instrument.html), launched in December 1997 and ended in August 2014.[17–19] It allows to detect both IC and CG lightning flashes with an efficiency around 90%, but does not distinguish between them. It has a 350 km low orbit around the Earth (402 km after an orbit boost in August 2001), a 600 km × 600 km field-of-view, and an inclination of 35°, which allows the coverage of a region of the Earth between latitudes 38°N and 38°S (blue rectangle in Figure 1). Due to the precession orbit, LIS is limited to roughly one overpass per day for any geographical location of the region covered. Its spatial resolution is between 3.9 and 5.4 km at nadir and limb, respectively.[16] During a single orbit LIS can observe a given point on the Earth's surface for between 80 and 85 s with a time resolution of 2 ms. During one year, the number of orbits is comprised between 5689 and 5704, depending on whether a leap year or not. The data used in this study are available on the NASA website (http://thunder.msfc.nasa.gov/data) and correspond to lightning flashes reconstructed from the optical events detected by LIS, successively associated to make groups and flashes according to time and space criteria. Thus, the information given for a flash consists in the time of occurrence, the number of events, that of groups, the measured radiant energy and the estimated location.

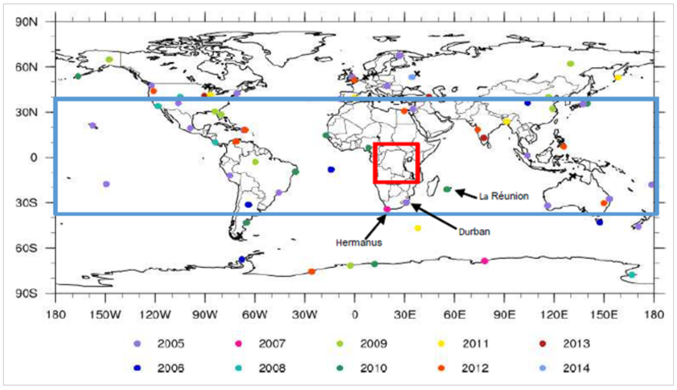

Figure 1 Map of the WWLLN stations around the world. The colour provides the installation year as indicated in the legend. The red rectangle displays the study area (15°S-10°N; 10°E-35°E) and the blue rectangle the latitude band covered by LIS (38°S-38°N).

Methodology

Reconstruction of flashes from strokes

Because the sensors of WWLLN detect the strokes, it is necessary to reconstruct the flashes. Cummins et al.[20] described a process to identify strokes associated with a given flash by considering time and space criteria for the data from NLDN. They associate successive strokes in a flash when they are separated by less than 10 km in distance and less than 0.5 s in time, with a maximum duration of 1 s for the flash. In our case, we test several criteria because the accuracy and the efficiency of WWLLN are different compared to NLDN ones. Figure 2 displays the ratio between the number of flashes and that of strokes for data from 2011, for two distinct time criteria (0.5 and 1 s) by considering variable distance criterion. It shows the curves for both values of dt are close, especially for values of distance lower than 20 km. On the other hand, the ratio changes more slowly with the distance, which means that the distance criterion can be taken beyond about 20 km without affecting much the number of flashes. Adopting the values 0.5 s and 20 km for the time and distance criteria respectively, an algorithm has been used to transform strokes data into flashes data for all nine years studied.

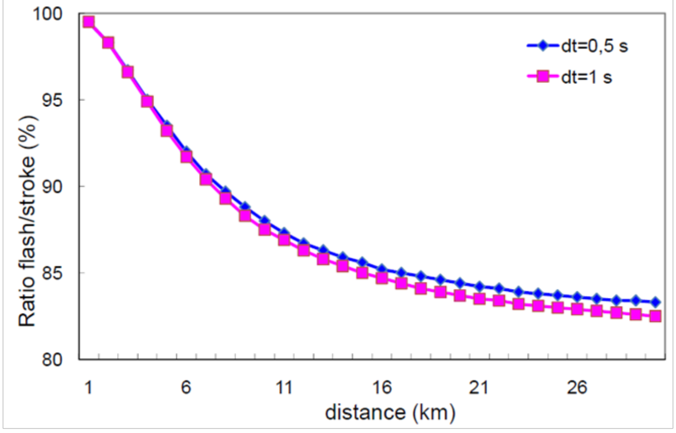

Figure 2 Ratio (%) between the number of WWLLN flashes and that of strokes as a function of the distance criterion for two distinct time criteria.

Method of calculation of detection efficiency

For a same flash, WWLLN and LIS can give different locations since they do not measure the same physical parameters: WWLLN detects the stroke at the ground and LIS detects the cloud top illumination. Furthermore they differently associate the events relative to their number, timing and location. This aspect has to be kept in mind when a comparison is made between both data collections. Another difference between both databases is the time of coverage for a given region: WWLLN has a continuous coverage everywhere in the study domain while LIS covers a given point of this domain for about 90 s.

The surface swept by the LIS sensor after recovery of different orbits corresponds to the latitude band of 38°S to 38°N (Figure 1). In this band, the elementary area is dS:

$$dS = R_T d\lambda \; R_T \cos\lambda \; d\varphi$$

Where λ is the latitude, φ is the longitude and RT is the Earth radius at the equator (RT = 6378 km).

By integrating on the latitude band:

$$S_A = R_T^2 \iint \cos\lambda \, d\lambda \, d\varphi = R_{T^2} \int_0^{2\pi} \Big(\int_{-38°}^{38°} \cos\lambda \, d\lambda \Big) \, d\varphi$$

$$S_A = 4\pi R_T^{\,2} \times 0.6157$$

During a leap year (31,622,400 s), the satellite TRMM covers 5704 orbits. Thus, the average duration of one orbit is 31,622,400 / 5704 = 5543.89 seconds. During one orbit, the area covered at the ground will be $S_0 = L \times 600\ km$

L is the length of one orbit (one revolution around the Earth): $S_0 = 40074 \times 600 = 24{,}044{,}400\ km^2$

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Then, we define a surface coefficient:

$$\alpha_S = \frac{S_0}{S_A} = \frac{24{,}044{,}400}{4\pi\ R_T^2 \times 0.6157} = 0.07639$$

During one orbit, i.e. 5543.89 s, the surface covered is therefore 7.64% of the surface SA. Furthermore, the satellite covers each point of this surface during only 90 s over the total 5543.89 s of the orbit. A time coefficient α_t has to be considered to estimate the proportion of the lightning activity that can be detected by LIS.

$$\alpha_t = \frac{90}{5544} = 0.0162$$

Thus, LIS sees each point of the surface covered during one orbit for 1.62% of the orbit duration. To summarize, during one orbit, LIS observes 7.64% (α_s) of the whole surface covered by the satellite during its successive passes and each surface point is observed during 1.62% (α_t) of the orbit duration. Consequently, the product $\alpha_s \times \alpha_t$ provides the time proportion during which a point is observed by LIS for the whole coverage of the band SA:

$$\alpha = \alpha_s \alpha_t = 0.0764 \times 0.0162 = 0.00124\ i.e.\ 0.124\ \%$$

This coefficient is applicable for any point of S_A and therefore for any point of the study area. We consider that statistically, according to the number of orbits described during one year, the sampling made by LIS is representative of the whole lightning activity for any region of the study area. Then we apply α to recover the total number of flashes NO produced within the area from the number of flashes detected by LIS N_L:

$$N_L = \alpha N_O,\ therefore\ N_O = N_L / \alpha$$

In order to evaluate the detection efficiency (DE) for WWLLN relative to LIS, we take into account this coefficient α by dividing the number NW of lightning flashes detected by WWLLN by the number of flashes N_O:

$$DE = \frac{N_W}{N_O} = \frac{N_W}{N_D} 0.00124$$

Results

Detection efficiency

The calculation of DE for each of the years 2005-2013 is included in Table 1 and compared with the detection efficiency DEB found by Bovalo et al.[5] for the South Western Indian Ocean (SWIO).

Table 1 Annual count of lightning flashes detected by WWLLN (N_W) and by LIS (N_L), extrapolated total lightning flashes from LIS over the whole year and the whole study area (N_O). Detection efficiency for the WWLLN relative to LIS for the study area (DE) and for the SWIO area (DE_B) from Bovalo et al.[5] Maximum value of the annual flash density from WWLLN (FD_{max}) and estimated by applying the DE factor (FD'_{max}).Average multiplicity M_m and proportion of flashes which produced only one stroke (M = 1)

	N_W	N_L	N_O	DE (%)	DE_B (%)	SD_{max} (day)	FD_{max} (km^{-2} y^{-1})	FD'_{max} (km^{-2} y^{-1})	M_m (str/fl)	M=1 (%)
2005	2,676,276	190,308	153,761,877	1.74	2.00	114	2.70	155.17	1.071	93.73
2006	2,516,580	188,449	152,259,873	1.65	3.40	154	1.90	115.15	1.127	88.99
2007	3,602,064	182,653	147,568,838	2.44	5.00	131	2.66	109.02	1.111	90.64
2008	2,467,176	183,466	148,233,792	1.66	4.70	130	1.91	115.06	1.095	91.94
2009	3,446,317	195,316	157,808,157	2.18	6.60	143	3.93	180.28	1.116	90.32
2010	3,643,387	188,984	152,692,134	2.39	8.30	157	4.41	184.52	1.142	88.43
2011	4,701,732	192,007	155,134,607	3.03	8.50	167	4.63	152.81	1.185	85.37
2012	6,550,235	182,560	147,501,778	4.44	-	167	8.22	185.14	1.219	82.98
2013	9,181,456	192,443	155,486,879	5.90	-	189	12.86	217.97	1.278	79.62

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The parameter DE increases year after year, except between 2005 and 2006, and between 2007 and 2009 since it markedly increases in 2007 and then decreases in 2008. From 1.65% in 2006 it increases to 5.90% in 2013. This evolution is roughly in agreement with the results of Bovalo et al.[5] for the SWIO with DE_B that increases from 2.0 in 2005 to 8.5 in 2011. However, the increase is larger for DE_B compare to DE over the common period 2005-2011 since from close values for both parameters in 2005 (~2), DE is about doubled while DE_B is multiplied by 4 in 2011. The increase for 2007 is more pronounced for DE than for DE_B. The global increase of the detection efficiency for WWLLN relative to LIS can be explained by an evolution of the network, or by the number of stations or by improving the algorithm of treatment used. According to Figure 1, it is difficult to consider the number of stations to explain the difference. As a matter of fact, the new stations installed during the period 2005-2011 (La Réunion, Hermanus) can improve the detection in both areas since they are at roughly equivalent distance. Furthermore a new station was installed close to DRC in 2010 in Nigeria (Figure 1). The effect of a new station can be more visible for the year after its installation, thus that installed in Nigeria will be more efficient for the flash amount on 2011, what is clearly shown in Table 1 since DE is 2.39 in 2010 and 3.03 in 2011. We have also to consider the different nature of the domains of both studies, mainly over the ocean for SWIO and over land for Congo Basin. The WWLLN may be more efficient to detect flashes over the ocean because the peak currents for CG flashes are generally larger and therefore easier to detect remotely.[21] The study by De Maria et al.[7] devoted to investigate the relationships between the changes in the intensity of tropical cyclones and their lightning activity over two ocean areas during the period 2005-2010, also shows an increasing DE of the WWLLN. However for both areas, the increase was faster than that estimated in the present study above land area. As a matter of fact, their total lightning DE was only about 1−3% in 2005 according the area, and increased to about 20% by 2010 for both areas.

Overall lightning activity

WWLLN data are used for the analysis of the lightning activity in the area including the DRC territory. Table 1 displays several parameters related to the lightning activity in the study area and year by year. The first and second columns indicate the number of flashes detected by the WWLLN (N_W) and LIS (N_L). Both flash numbers are also displayed in Figure 3 in order to visualize their respective evolution during the period of study and with comparable scales. A first look at the time series of N_W shows a first period of four years with a roughly constant amount of flashes except for 2007 that exhibits a specific increase. After 2008 N_W increases significantly and continuously to reach in 2013 about 3.5 times the value of 2005 (from 2,676,276 in 2005 to 9,181,456 in 2013). On the contrary, the number of flashes detected by LIS in the study area varies little and no tendency is observed during the period. As a matter of fact, the minimum is 182,560 in 2012 while the maximum is 195,316 in 2009 (Table 1). N_L varies weakly during the whole nine-year period. Since the LIS detection ability did not change during the period, we can estimate the lightning activity did not change significantly.

The increase of the number of flashes detected by the WWLLN is mainly due to an improvement in the detection efficiency (DE) during the same period. Several reasons can be evoked for such improvement: more stations were operated and the processing algorithm was more efficient.[13] Thus, before using WWLLN data to study the Lightning climatology in the Congo Basin, a first step is to find a method to determine the relative detection efficiency of WWLLN in the study area since that of LIS is estimated for any region of the world.[18]

The increase of DE is not uniform over the whole Congo Basin. This fact is illustrated in Figure 4 which displays increase of DE, for 2013, in two areas mostly active in Congo Basin defined as Zone max and Zone centre by their geographic coordinates as follow:

$$\begin{array}{ll} \textit{Zone centre}: & \textit{Zone centre}: \\ 18 \le \textit{Longitude} \le 23 & 18 \le \textit{Longitude} \le 23 \\ -4 \le \textit{Latitude} \le 1 & -4 \le \textit{Latitude} \le 1 \end{array}$$

The numbers of flashes detected by the WWLLN in these areas (WWLLN Zone max and WWLLN Zone centre) and LIS (LIS Zone max and LIS Zone centre) are also shown in Figure 4.

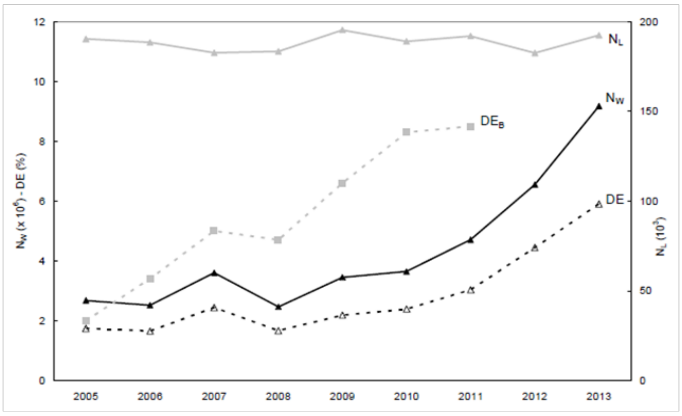

Figure 3 Annual number of flashes detected by the WWLLN (N_W) and that detected by LIS (N_L), and estimated detection efficiency for WWLLN data relative to LIS data (DE) and that from Bovalo et al.[5] (DE_B) for SWIO.

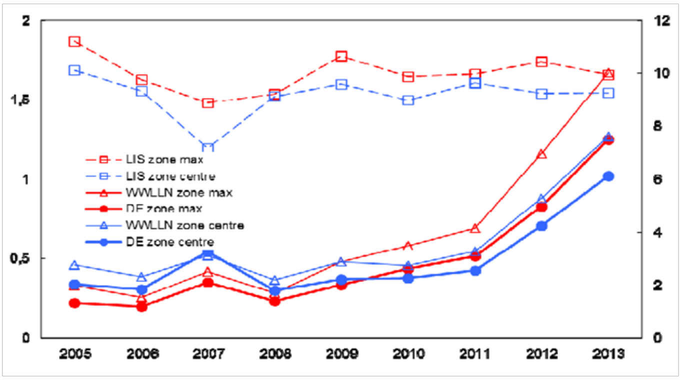

Figure 4 Comparison of DE Zone max and DE Zone centre. Numbers of flashes detected by the WWLLN (WWLLN Zone max and WWLLN Zone centre) and LIS (LIS Zone max and LIS Zone centre) in Zone max and Zone centre.

Annual lightning activity

Figure 5 displays the annual evolution of the proportion of the flashes monthly detected by the WWLLN over the area. The histogram displays the proportion of the monthly activity averaged over the 9-year period. Two curves display the extreme values of this proportion within a 95% confidence interval in order to show the variability over the whole period. The average value smooths the fluctuations from year to year and the dispersion around this average is included between 12% and 25% in relative values. For each year the same cycle is observed. Thus, a minimum of lightning activity is clearly identified during the months of June, July and August with a proportion of lightning activity around 4%. The maximum activity is over a period centered around December-January and of variable duration according to the year considered. According to the average monthly activity in Figure 5, the period of the maximum lasts about six months from October to March.

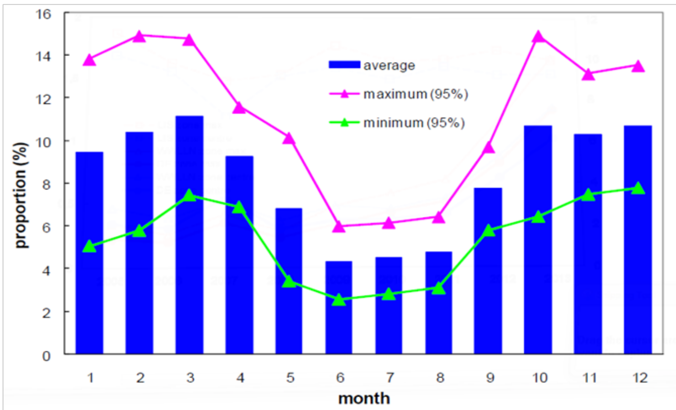

Figure 5 Annual evolution of the monthly proportion of WWLLN flashes (%) averaged over the 9-year period (histogram), with indication of the 95% confidence interval (upper limit in rose and lower limit in green).

According to Figure 3, the number of flashes detected by the WWLLN significantly increases in 2007 and continuously from 2009. We compared the monthly flash number, month by month, between 2007 and 2006 on one hand, and between 2007 and 2008 on the other hand. In the present case, the irregularity of the flash number for a same month, from one year to another, does not allow to bring out the main reason of the increase of the number of flashes for 2007. Several reasons can explain this irregularity, as for example the natural variability of the storm activity or the breakdowns of some stations. On the same way, the same reasons do not allow to locate in time an improvement in DE at this scale of the month between 2009 and 2013.

Figure 6a displays the distribution of the flashes detected in 2013 versus the multiplicity and Figure 6b displays the evolution of the mean multiplicity Mm and that of the proportion of flashes with a multiplicity equal to one, i.e. the proportion of flashes with only one stroke detected. First of all, we can note the multiplicity is low, between 1.078 in 2005 and 1.278 in 2013. As a matter of fact, it is much lower than the multiplicity usually found for regional networks since it is close to 2 for the -CG flashes and a little higher than 1 for +CG flashes, like in the US with the NLDN,[22] or like in other regions of the world.[21,23] Secondly, the mean multiplicity increases when more flashes are detected, i.e. when DE increases as indicated in Figure 6b. As a matter of fact, except for 2007, the increase of Mm is consistent with the increase of DE shown in Table 1, while the proportion of flashes with M=1 obviously decreases. Thus, the increase of DE leads to detect more flashes, as seen above, and more secondary strokes.

Discussion and summary

The lightning activity issued from the WWLLN during a period of nine years has been analysed for an area of Central Africa including DRC, small surrounding countries and parts of others. This area corresponds to longitudes between 10°E and 35°E, latitudes between 15°S and 10°N, i.e. about 2750 km × 2750 km, and covers different types of relief between the sea level in the western part and mountain ranges exceeding 3000 meters for some or 4000 meters for others, in the eastern part. The detection system used in the WWLLN records a proportion of strokes produced by lightning flashes and a first step consist in gathering strokes issued from a same flash according to time and space criteria. Tests on several values of these criteria between two successive strokes of a same flash leads to validate 0.5 s for the maximum time difference and 20 km for the distance. The distance criterion is larger than those usually found in the literature for regional detection networks, as for example 10 km proposed by Cummins et al.[20] for the US NLDN, and Mäkelä et al.[24] for the ALDIS network in northern Europe. This distance criterion usually corresponds to the maximum error of location of a stroke[25] but for the present long range detection network WWLLN the error of location is obviously larger than 10 km. For the time criterion, it is of the same order than that for regional networks, usually fixed at 0.5 s between two successive strokes,[20] the baseline of the network has no influence on this parameter.

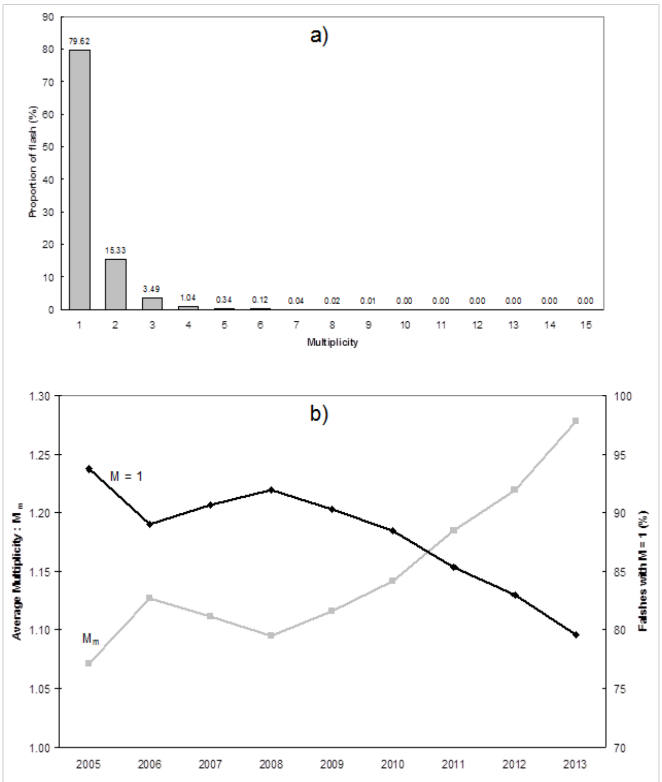

Figure 6

a) Distribution of the WWLLN flashes versus multiplicity in 2013.

b) Mean multiplicity M_m and proportion of WWLLN flashes with a multiplicity equal to 1 from 2005 to 2013.

The criteria here considered for gathering strokes have been applied for each year of the studied period in order to focus on the number of flashes. Several parameters in relation with the flashes provided by the WWLLN change over the 9-year considered period, especially after 2008. For example the number of flashes is around 2,500,000 in the first four years and increases regularly from 2009 to reach 9,181,456 in 2013. The proportion of flashes with only one stroke decreases from about 90% during the first years to 80% in 2013, while the average multiplicity is around 1.1 at the beginning of the period and close to 1.3 at the end. The evolution of all these parameters is interpreted in terms of detection efficiency improvement by comparing with data provided by LIS during the same period over the same area. As a matter of fact, the total number of flashes detected by this space sensor is almost constant year after year. The sample can be considered large enough since the yearly flash number from LIS is around 188,000. Its variation does not exceed more than 4% of this value. The total amount of flashes that LIS could detect by continuous observation of the study area is estimated from a simple space and time integration of data acquired by the orbiting sensor. It is estimated that the sensor detects only 0.124% of the total lightning flashes. The detection efficiency of the WWLLN relative to LIS evolves from ~ 2% during the first four years to ~ 6% in 2013. The trend is the same as in other parts of the world. By comparing with ocean regions, it is lower and it increases less rapidly. For example in SWIO, Bovalo et al.[5] found 8.5% for 2011 while the present study provides a value close to 3%. Likewise, DeMaria et al.[7] showed the WWLLN DE over two ocean basins increased faster during the period 2005-2010, from about 1% to 20% for East Pacific and from 3% to 20% for Atlantic. Rudlosky et al.[26] analysed also the detection efficiency over a large area of western hemisphere during the period 2009-2012. They found the smallest values over land increasing from 4% to 6.4% during the period, large values over ocean increasing from 12.3% to 17.3%, with the largest values over north hemisphere (10.7% in 2012 while it is 4.9% over south hemisphere). The present study gives 4.44% in 2012 for a land area mainly located in south hemisphere which is consistent with other observations. It is to be noted that the detection efficiency is 44% higher in 2007 compared with previous or next year. Other studies confirm this tendency as Bovalo et al.[5] and Rodger et al.[13] who found an increase of 47% and of about 63%, respectively for the whole Earth because of the use of a new algorithm.

The annual cycle of lightning activity exhibits a period of high activity between October and March, during which about 10% of the total lightning flashes are produced each month, and a period of low activity from June to August with about 4.5% of the total flashes produced each month.

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Conflict of interest

Authors declare there is no conflict of interest.

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