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Comparison of lightning activity in the two most active areas of the Congo Basin

Jean K. Kigotsi[1, 2], Serge Soula[1], Jean-François Georgis[1]

[1]Laboratoire d'Aérologie, Université de Toulouse, CNRS, Toulouse, France
[2]Département de Physique, Faculté des Sciences, Université de Kinshasa, République Démocratique du Congo

Correspondence to: Jean K. Kigotsi (jeankigotsi@gmail.com); Serge Soula (serge.soula@aero.obs-mip.fr)

Abstract. A comparison of the lightning activity in the two most active areas (Area_max for the main maximum and Area_sec for the secondary maximum) in the Congo Basin is made with data obtained by the WWLLN during 2012 and 2013. Both areas of same size (5° × 5°) exhibit flash counts in a ratio of about 1.32 for both years and very different distributions of the flash density with maximum in a ratio of 1.941 and 2.585 for 2012 and 2013, respectively. The diurnal cycle is much more pronounced in Area_max than in Area_sec with a ratio between the maximum and the minimum of 15.4 and 4.7, respectively. However, the minimum and maximum of the hourly flash rates are observed roughly at the same time in both areas, between 07:00 and 09:00 UTC and between 16:00 and 17:00 UTC, respectively. In Area_sec the number of days with very low activity (0-1000 flashes per day) is very large (164 days) and that with larger activity decreases very rapidly. In Area_max the number of day decreases more slowly and is larger for most of levels of lightning activity. The correlation at the daily scale between the lightning activity in Area_max and that in Area_sec is weak but positive. In summary, the thunderstorm activity in Area_sec is more variable at different scales of time (monthly and daily), in intensity and in location.

1 Introduction

According to several studies about the lightning climatology around the Earth, the Congo Basin is considered as the most active region with either a large maximum or two distinct ones (Christian et al., 2003; Albrecht et al., 2011, 2016, Cecil et al., 2014, Soula et al., 2016). Actually, the features of the maximum area depend on the space resolution considered in the calculation of the flash density and the scale resolution in the graphic representation. For instance, Cecil et al. (2014) provided two maps of the lightning density from Lightning Imaging Sensor (LIS) and Optical Transient Detector (OTD) data with different resolutions, 0.5° and 2.5° and a scale with a larger dynamic for large values. With a 0.5° resolution two maxima are distinguished in the region of Congo Basin and only one with a 2.5° resolution. Two separated maximums are also visible in the study by Christian et al. (2003) with a resolution of 0.5° and a non linear scale of density. However, in the latter study, both maximums do not remain along the year by considering the lightning activity at the scale of the 3-month season. Recently, Soula et al. (2016) showed a very sharp and localized maximum in the annual and seasonal lightning density in eastern Democratic Republic of Congo (DRC) from World Wide Lightning Location Network (WWLLN) data with a 0.1° resolution and a linear scale. In this study, a secondary maximum was also highlighted west of the main maximum, especially during the first part of the 9-year period of study. This secondary maximum was less pronounced and more scattered in a large area. In this study the region of maximum could be analyzed in detail because the linear scale of density values was better adapted for large values compared to previous studies. Recently, Albrecht et al. (2016) classified the most active regions of the world in terms of lightning activity by using LIS data at a resolution of 0.1°. The existence of two regions of maximum was also displayed but the non linear scale did not allow a quantitative comparison of the maximum values. However, they considered the locations of the first ten lightning hotspots over the whole African continent and they showed most of them including the strongest ones are located in DRC.

The results of Soula et al. (2016) provided the following characteristics. The main maximum flash density is observed every year in one small region of the DRC, at about 28°E and between 1°S and 2°S. This maximum is embedded within a region of large values of lightning flash density strongly contrasting with the whole study area. The extension of this region is approximately 300 km north-south and 200 km east-west. It is located in the area where many authors identified the maximum of the planetary lightning activity, as Christian et al. (2003) who falsely attributed it to Rwanda, Cecil et al. (2014) and Albrecht et al. (2011). The high space resolution and the linear scale used in Soula et al. (2016) allowed to better localize it and specify its shape and amplitude characteristics. In addition, the maximum number of days with thunderstorms has been found in the same area (189 days of storms in 2013) as the average number of flashes per day of storms (approximately 8 flashes per day). Another area of large flash density considered as a secondary maximum was pointed out in Soula et al. (2016). This area was broader but less contrasted from year to year during the period of the study. It roughly extends from the centre of DRC to Congo to the west and to Angola to the south.

The goal of this study is to compare the characteristics of lightning activity in the two areas of maximum. The second section describes the data and the methodology used, the third section presents the results from several comparisons, and the fourth section is devoted to a discussion.

2 Data and methodology

By following the study by Soula et al. (2016), we define two areas of equal dimension, one for the main maximum considered as "Area_max" and the other for the secondary maximum considered as "Area_sec". They are identified by latitude and longitude values in the following intervals:

[25°E; 30°E] and [4°S; 1°N] for Area_max

[18°E; 23°E] and [4°S; 1°N] for Area_sec

We use data from the WWLLN collected during 2012 and 2013. According to the continuous increase of the detection efficiency from 2005 to 2013 observed by Soula et al. (2016) in the total domain of the study, we select the two last years of the period for a comparison between both areas Area_max and Area_sec.

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) (Dowden et al., 2002). 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. Since its implantation in March 2003, the WWLLN has been improved in terms of number of stations and development of the processing algorithm (Rodger et al., 2008). In 2014, it had more than 60 sensors spread on the planet (Soula et al., 2016).

3 Results

3.1 Spatial distribution of the lightning activity

Figure 1a-b shows the lightning density, in flash km^{-2}, calculated with a resolution of 0.05° from WWLLN data in the large domain of Congo Basin for 2012 and 2013, respectively. Figure 1c-d shows the number of days of the year with thunderstorm activity in the same domain with a same resolution for 2012 and 2013, respectively. The white frames indicate the

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two areas with strong activity (left Area_sec and right Area_max). Table 1 displays the count of flashes, the maximum value of the density for both areas and each year. Both areas of same size (5° × 5°) exhibit flash counts in a ratio of about 1.32 for both years, which indicates an almost stable from one year to the other. On the contrary, the ratio of the maximum flash density is very different from one year to the other, since it is 1.941 and 2.585 for 2012 and 2013, respectively. This difference can be easily understood since the maximum value is very local and can change substantially from one year to the other, and furthermore the space resolution used in the study is very high, with a value of 0.05°. The maximum value of the density depends on the space resolution, in the sense that it increases when the resolution becomes higher. By comparing with the values reported by Soula et al. (2016) for a resolution of 0.1°, it is clear that the maximum of the density is larger for 0.05°. Thus it rises from 12.86 to 15.33 flashes km^{-2} for 2013 and from 8.22 to 8.62 flashes km^{-2} for 2012. On the other hand, the maximum number of stormy days is lower with the resolution of 0.05°, from 189 to 125 days for 2013 and from 167 to 99 days for 2012.

The difference between the distributions in the two areas appears also clearly regarding both lightning density and number of days of the year with lightning activity in Figure 1. Indeed, the highest values of both parameters are located in the same region of the 5° × 5° frame for Area_max while they are much more scattered in the frame for Area_sec. The contrast between both areas is stronger for the lightning density compared to the number of day with thunderstorm, which means the number of flash par day with thunderstorm is larger for Area_max. It means that the storms in Area_max are more active and/or more stationary, and/or more numerous. The differences observed in the maximum values and the distributions of the lightning density indicate specific and local conditions for the thunderstorm development in Area_max. These conditions are the presence of a mountain range that exceeds 3000 meters (28.75°E; 1.5-2.2°S), on one side of which the lightning density markedly increases, and the presence of the lake Kivu (29.2°E; 1.9°S) above which the lightning density increases. No specific shape of the lightning density or stormy day is visible in Area_sec.

3.2 Diurnal activity

Figure 2 shows the daily cycle of the amounts of flashes detected by WWLLN in Area_max and Area_sec. These amounts are calculated over one hour and averaged over all days of 2013. The time scale of the graph is made so that the amounts are associated to the beginning of the 1-hour period of calculation. Both areas exhibit the same type of evolution with a large proportion of flashes during the afternoon. The minimum and maximum numbers of flashes are observed roughly at the same time in both areas, in the morning between 08:00 and 09:00 UTC for Area_max and between 07:00 and 08:00 UTC for Area_sec, and in the afternoon between 16:00 and 17:00 UTC, respectively. But the contrast between the morning minimum and the afternoon maximum is stronger for Area_max (ratio of 15.4) than for Area_sec (ratio of 4.7). It means the diurnal cycle is much more pronounced in Area_max. Consequently, while the lightning rate is larger in Area_max for the main part of the day it is lower during a short interval between 06:00 and 10:00 UTC corresponding to the minimum activity in both areas.

3.3 Annual variability

We compare the lightning activity in both areas in terms of daily distribution of the flashes detected during one year. The year of reference is 2013 with a total of 362 days available in the database. The flash count is performed day by day in each area and then the days are classified by range of flash numbers. Thus, Table 2 displays the result of the classification for each area over 12 classes of flash number. The incrementing of each class is done on 1,000 flashes, from 1-1000 for CL1 to more than 10,000 for CL11. The first class CL0 corresponds to days without any flash detected. To make easier the interpretation of the results, they are also plotted in the graph of Figure 3.

The number of days without any flash (CL0) is much larger for Area_sec than for Area_max (7 and 0, respectively). For CL1 corresponding to the lower flash numbers, the number of day is also larger for Area_sec, about two times that of Area_max, 157 and 84, respectively. On the contrary, the number of days for classes corresponding to intermediate flash numbers (CL2 to CL6, from 1,001 to 6,000 flashes per day) is significantly larger for Area_max for the cumulative number of days (248 against 168) and for each class considered separately. For the classes with very high activity (CL7 to CL11, more than 6,000 flashes per day) the number of days is small and not very different in both areas for each class and even equal for the cumulative number of days (30 days).

3.4 Variability during periods of low and high activity

By considering the lightning activity during a period of 9 years, Soula et al. (2016) pointed out a clearly low activity during three months June-July-August and a six-month period of high activity covering the months of January-March and October-December. We now investigate in each area, the daily flash number during these two distinct periods for 2013

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defined as high activity period (HAP) including 179 days of data and low activity period (LAP) including 92 days of data. The result is presented in Table 3 and illustrated in Figure 4. During both periods the general trend is the same as for the annual variability obtained over 362 days. The number of days with few lightning flashes (CL0-CL1) in Area_sec is twice that in Area_max for both periods. On the contrary, the number of days with intermediate amounts of lightning flashes (CL2-CL5) is larger in Area_max, also about in the same proportion for both periods. Finally, the number of days with a number of flashes exceeding 5000 flashes (CL6-CL11) is small and almost equal in both areas, for each period. In particular, during LAP it is one day at the more, as indicated in Table 3 and Figure 4. It is also to be noted that for each area, the ratio between the number of days during HAP and LAP is very strong from CL5 to CL7 (CL8 for Area_sec), with a maximum value of about 10 for CL6. During HAP, whatever the area considered, the proportion of the number of day characterized with a flash number lower than 5000 is about 83%, whereas during LAP, it is about 95%.

3.5 Correlation between daily lightning activities

In order to evaluate the simultaneity between lightning activity in Area_max and Area_sec, we display the graph of correlation between the daily lightning flash amounts for both areas and in 2013. These daily amounts are calculated in two ways, first by considering the calendar day (00h00 – 24h00 UT) and then according the daily cycle of lightning activity between two minimums (06h00 – 06h00 UT, see Figure 2). Figure 5 shows the result of this correlation study: (a) for the calendar days and (b) for the lightning cycle days.

In the first case the correlation coefficient R is 0.34 and in the second case it is 0.25. Thus, the correlation is weak but positive, that is to say the tendency is that when the daily flash number increases for one area it also does for the other. At first glance, both distributions are similar. They reflect the trend highlighted by Figures 3 and 4 insofar as the low values ($\leq$ 1000 flashes) are more numerous in Area_sec. Inversely, the intermediate values are more numerous in Area_max with 230 days with flashes between 1,001 and 5,000 against 156 in Area_sec. For the values exceeding 10,000 flashes, there are 7 days for Area_max and 5 days for Area_sec in Figure 5a. In Figure 5b, these values are 6 and 8, respectively, which means there are more days with a large number of lightning flashes in Area_sec, by considering the daily cycle of the lightning activity. This observation is consistent with the fact that the lightning activity is more spread during the day in Area_sec as indicated in Figure 2. Thus, by considering the day according the lightning activity, the episodes of strong lightning activity in this area are less likely to be cut.

3.6 Monthly activity

Figure 6 shows the monthly proportions of flashes detected in Area_max and Area_sec during 2012 and 2013. The minimum proportion is found in August and in Area_sec (between 3 % and 4 %) for both years. The maximum proportion is also found in Area_sec in May for 2012 (about 14%) and in December (about 14%) for 2013. These two characteristics show that the variability is always stronger in Area_sec than in Area_max although the distribution is different from 2012 to 2013 for both areas. For example, in April it is 6.1% and 11.3% for Area_max, 5.7% and 9.4% for Area_sec, in 2012 and 2013, respectively. Inversely in May, the proportion of each area is much lower in 2013 compared to 2012 (4.7% and 8.1% for Area_max, 7.9% and 13.9% for Area_sec). For a given month, the respective proportions for Area_max and Area_sec remain in the same order, except for the first three months of the year.

4 Discussion

Albrecht et al. (2016) studied the lightning hotspots over the Earth. They found that six out of the ten most active spots over the whole African continent, including the three strongest ones, are located in an area corresponding to Area_max while only two are located in an area corresponding to Area_sec. Our results confirm the predominance of the larger lightning density in Area_max. The characteristics of the diurnal cycle observed in Area_max and Area_sec are consistent with Laing et al. (2011). These authors analyzed the cycle of the deep convection over a large area of tropical Africa including both areas of our study and during 2000-2003. They found the location of a sharp maximum of the average hourly frequency of coldest clouds in eastern DRC corresponding to Area_max, for two of the considered time intervals, 14:00-15:00 UTC and 17:00-18:00 UTC. They noted this maximum for two considered months April and October. They showed that during the time interval 05:00-06:00 UTC, thunderstorm activity is minimum in the part of DRC that corresponds to both areas of our study. In Albrecht et al. (2016) for the study of lightning hotspots, the daily cycles are considered for different locations of our areas. They found also a more pronounced daily cycle for the locations included in Area_max compared to the locations included in Area_sec.

The comparison of the monthly activity in Area_max and Area_sec in 2012 and 2013 suggests that the seasonal contrast is stronger in Area_sec where the maximum monthly amounts are observed in May and December respectively, and the minimum in August for the two years. A result for 2011 not presented here corroborates this feature. Even in these three years the minimum proportion is always in August and in Area_sec (about 3 to 4%). The maximum proportion is also in Area_sec but on different months (from 14 to 16%). So the seasonal contrast is much stronger in Area_sec than in Area_max. This result, due to the migration of the Intertropical Convergence Zone (ITCZ), is consistent with the contrast of the seasonal variation in lightning activity found in Soula et al. (2016). Area_max is less impacted by the migration of the ITCZ because the triggering of thunderstorms in this area has a very local origin.

The positive correlation observed between the daily activities of the two areas means there may be an influence between them or a common cause to explain the storm activity. However, the low value of the correlation coefficient indicates the activities can be different on the quantitative aspect. The most natural influence that could be assumed between the two areas would probably result from storms propagating from east to west. Propagation of conditions favourable to the development of thunderstorms, as instability of the atmosphere, could be also involved. Indeed, Laing et al. (2011) showed convection over equatorial Africa can be modulated by different conditions at synoptic scale for local occurrence or propagation of mesoscale convective systems. They especially mentioned the eastward-moving equatorially trapped Kelvin waves, the south-westerly monsoonal flow and the midlevel easterly jets. It is therefore consistent to obtain a low correlation between our two areas characterized by a strong annual storm activity. Furthermore, the correlation study is done at the scale of the day and as most thunderstorms develop at the end of the day, storm activity can occur during the following day in Area_sec that is several hundred kilometres to the West.

The distribution of storms in the Congo Basin mainly results from four contributions, namely: development, propagation, merging and regeneration of thunderstorms. As thunderstorms can develop everywhere in the Congo basin, they can naturally form in both Area_max and Area_sec. However, the great lakes and numerous mountains of Rift valley close to Area_max offer most favourable conditions for development and enhancement of thunderstorms. The most intense storms, at planetary scale, are found in the Congo Basin (Zipser et al., 2006). Area_max is probably the most active region in the world in terms of thunderstorms since the number of days of the year with thunderstorm activity is found to be maximum there (Figure 1c-d) and the density of lightning is large over this extended area (Soula et al., 2016). On the other hand, according to previous studies, Equatorial Africa thunderstorms spread from east to west basin (Laing et al., 2011; Nguyen and Duvel, 2008; Laing and Fritsch, 1993). Then thunderstorms may propagate from Area_max to Area_sec but different processes as merging and regeneration may affect their intensity and induce different characteristics in these areas. Several studies have shown that heterogeneity of soil moisture or vegetation play a role in thunderstorms triggering (Taylor et al., 2011; Garcia-Carreras et al., 2010). Furthermore, the modelling results of the Global Land Atmosphere Coupling Experiment (GLACE) classified Equatorial Africa, including Area_max and Area_sec, among the regions of high coupling between atmosphere and soil moisture (Koster et al., 2004). Thus, differences of soil moisture and/or vegetable cover between Area_max and Area_sec may contribute to the contrast between lightning activities of the two areas.

Farnsworth et al. (2011) pointed out that convective mesoscale systems (MCSs) constitute the fundamental unit of vertical energy transport in Central Africa. In other words, convection in this region generally leads to the formation of MCSs. This observation is consistent with the results of Liu and Zipser (2005) on deep convection in Congo basin. They showed convection in Congo basin frequently overshoots tropopause. Climatology of MCSs in Equatorial Africa, including the whole Congo Basin, was presented in Jackson et al. (2009). From five years series of data, these authors have shown that the zone on horseback at the equator between 5°S and 5°N and extending from the Atlantic coast to the west of the high mountains of the Rift Valley is the most active in terms of storm activity because it includes three of four maxima of number of MCSs that they have identified. In our study, Area_max coincides with the region where Jackson et al. (2009) found one of the two main cores of the maximum number of MCS. Area_sec has a less pronounced maximum of number of MCS and a larger number of lightning flashes per MCS in Jackson et al. (2009), which means a substantial proportion of lightning flashes are not produced by MCS in Area_max. Therefore, differences exist also in terms of thunderstorm activity between Area_max and Area_sec.

5 Conclusion

The space and temporal characteristics of the lightning activity are analysed in two areas of the Congo basin, Area_max with the stronger thunderstorm activity and Area_sec with a lower one. First, the lightning flashes are much more concentrated in a same part of Area_max from year to year, while they are more scattered in Area_sec. Secondly, the frequency of days with low activity is larger in Area_sec and the frequency of days with high activity is larger in Area_max. However, the frequency of days with very high activity is close in both areas and even the largest daily flash numbers are detected in Area_sec. Thirdly, a stronger contrast between the maximum and the minimum in the daily cycle is observed in

Area_max with a ratio of about 15.4 while it is only 4.7 for Area_sec. In conclusion, the thunderstorm activity is more variable in Area_sec, in terms of location, daytime of occurrence, seasonal distribution and intensity in terms of number of flashes.

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Table 1. Flash count and flash density in both areas.

	Flash count		Maximum flash density (fl km^{-2})	
	2012	2013	2012	2013
Area_max	696,144	1,000,687	8.62	15.33
Area_sec	526,278	760,405	4.44	5.93
ratio	1.323	1.316	1.941	2.585

Table 2. Number of days corresponding to classes of flash number in both areas during 362 days of 2013.

Flash number	CLASS	Number of day	
		Area_max	Area_sec
0	CL0	0	7
1 – 1,000	CL1	84	157
,1001 – 2,000	CL2	79	58
2,001 – 3,000	CL3	70	52
3,001 – 4,000	CL4	43	29
4,001 – 5,000	CL5	38	17
5,001 – 6,000	CL6	18	12
6,001 – 7,000	CL7	12	11
7,001 – 8,000	CL8	7	10
8,001 – 9,000	CL9	2	2
9,001 – 10,000	CL10	2	2
> 10,000	CL11	7	5

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Table 3. Number of days corresponding to lightning classes in the two maximum zones during the year 2013 for periods of high activity (HAP) and low activity (LAP).

Flash number	CLASS	Number of day (%)			
		Area_max		Area_sec	
		HAP	LAP	HAP	LAP
0	CL0	0	0	4 (2.2)	3 (3.3)
1 – 1,000	CL1	35 (19.6)	24 (26.1)	73 (40.8)	47 (51.1)
1,001 – 2,000	CL2	29 (16.2)	29 (31.5)	27 (15.1)	20 (21.7)
2,001 – 3,000	CL3	39 (21.8)	18 (19.6)	24 (13.4)	9 (9.8)
3,001 – 4,000	CL4	22 (12.3)	11 (12.0)	12 (6.7)	6 (6.7)
4,001 – 5,000	CL5	25 (14.0)	7 (7.6)	8 (4.5)	2 (2.2)
5,001 – 6,000	CL6	11 (6.1)	1 (1.1)	9 (5.0)	1 (1.1)
6,001 – 7,000	CL7	8 (4.5)	1 (1.1)	7 (3.9)	1 (1.1)
7,001 – 8,000	CL8	2 (1.1)	1 (1.1)	8 (4.5)	1 (1.1)
8,001 – 9,000	CL9	1 (0.6)	0	2 (1.1)	0 (0)
9,001 – 10,000	CL10	2 (1.1)	0	1 (0.6)	1 (1.1)
> 10,000	CL11	5 (2.8)	0	4 (2.2)	1 (1.1)

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-105
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 12 June 2017

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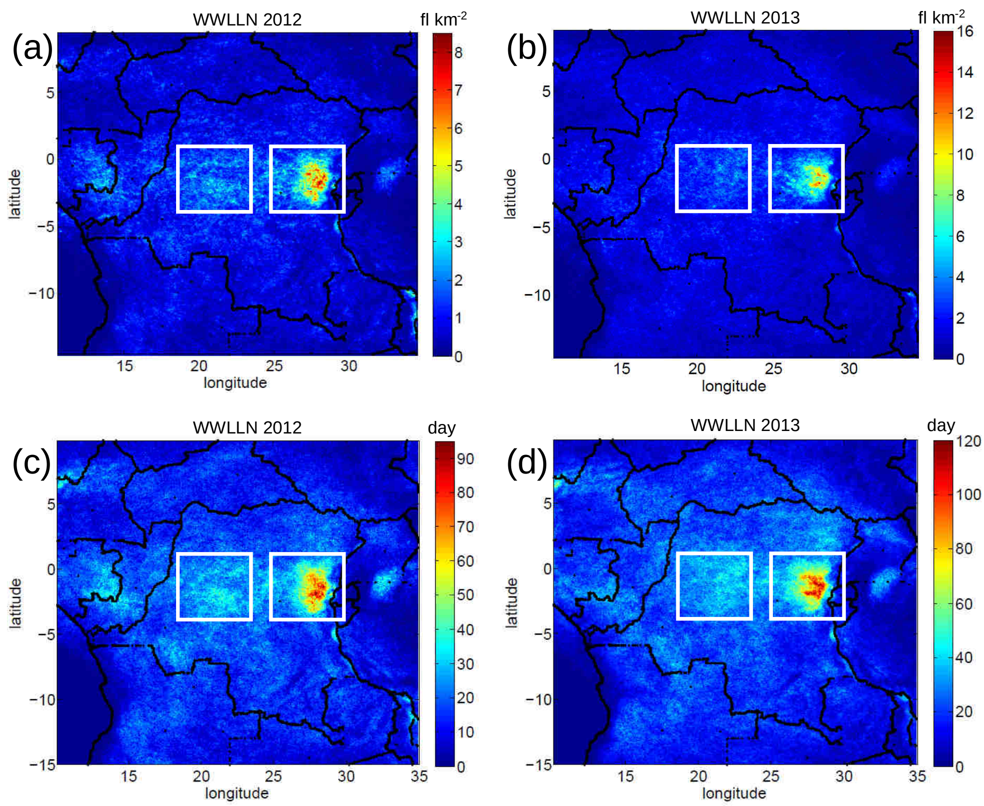

Figure 1. (a) and (b) Lightning density in flash km^{-2} calculated at a resolution of 0.05° from WWLLN data in the area of Congo Basin for 2012 and 2013, respectively. (c) and (d) Number of days of the year with thunderstorm activity in the same area with a resolution of 0.05° for 2012 and 2013, respectively. The white frames indicate the two zones with strong activity (left Area_sec and right Area_max).

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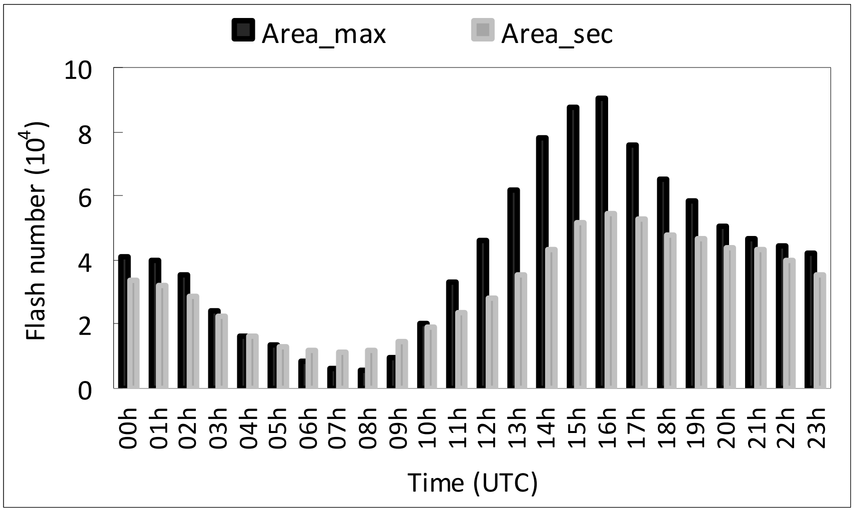

Figure 2. Evolutions of the lightning flash amounts in Area_max and Area_sec for 2013.

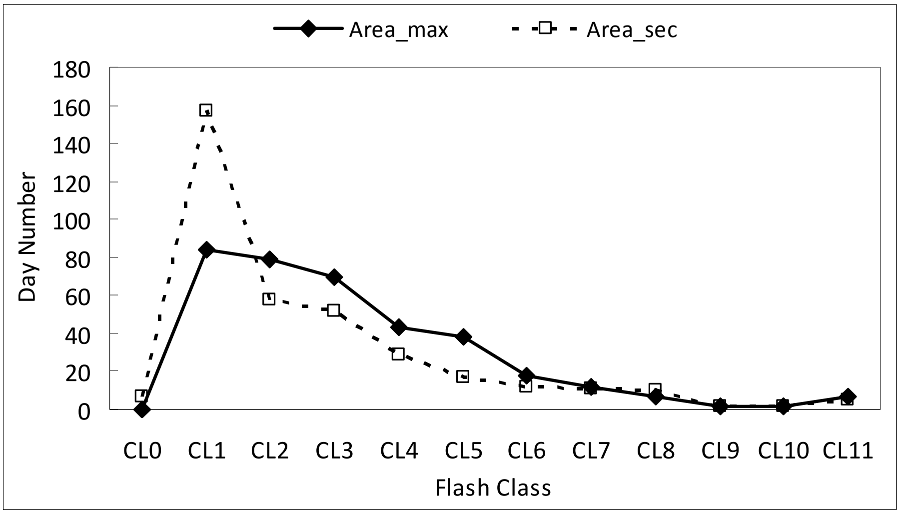

Figure 3. Distribution of the number of days versus the classes of flash number in both areas for 362 days of 2013.

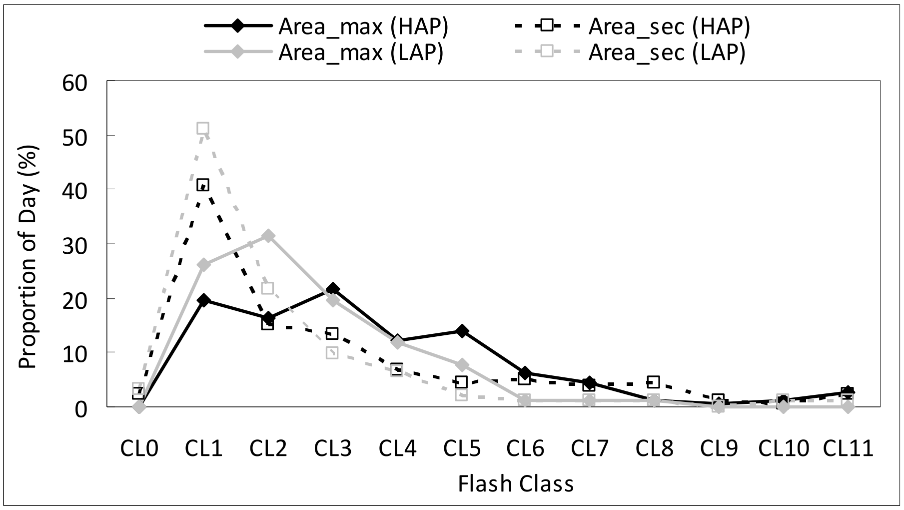

Figure 4. Distribution of the number of days versus the classes of flash number in both areas for two periods of 2013, low activity period (LAP) and high activity period (HAP).

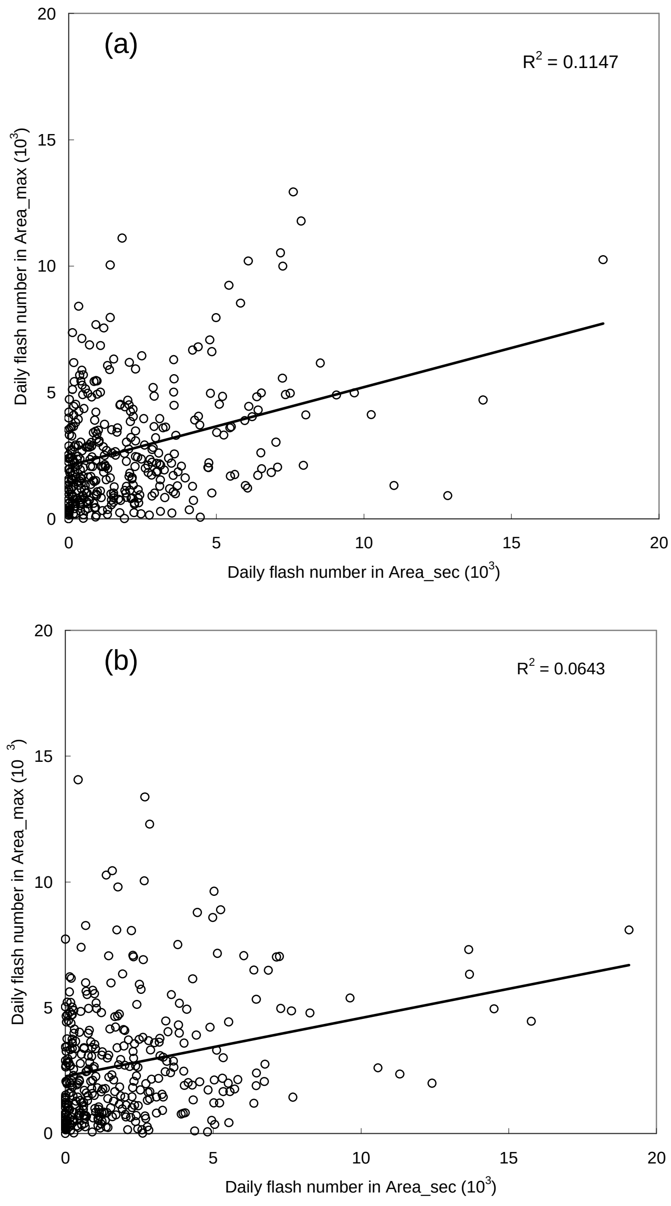

Figure 5. Diagrams of correlation between daily numbers of lightning flashes for Area_max and Area_sec in 2013: (a) at calendar daily scale (00h00-24h00 UTC) and (b) at lightning activity daily scale (06h00-06h00 UTC).

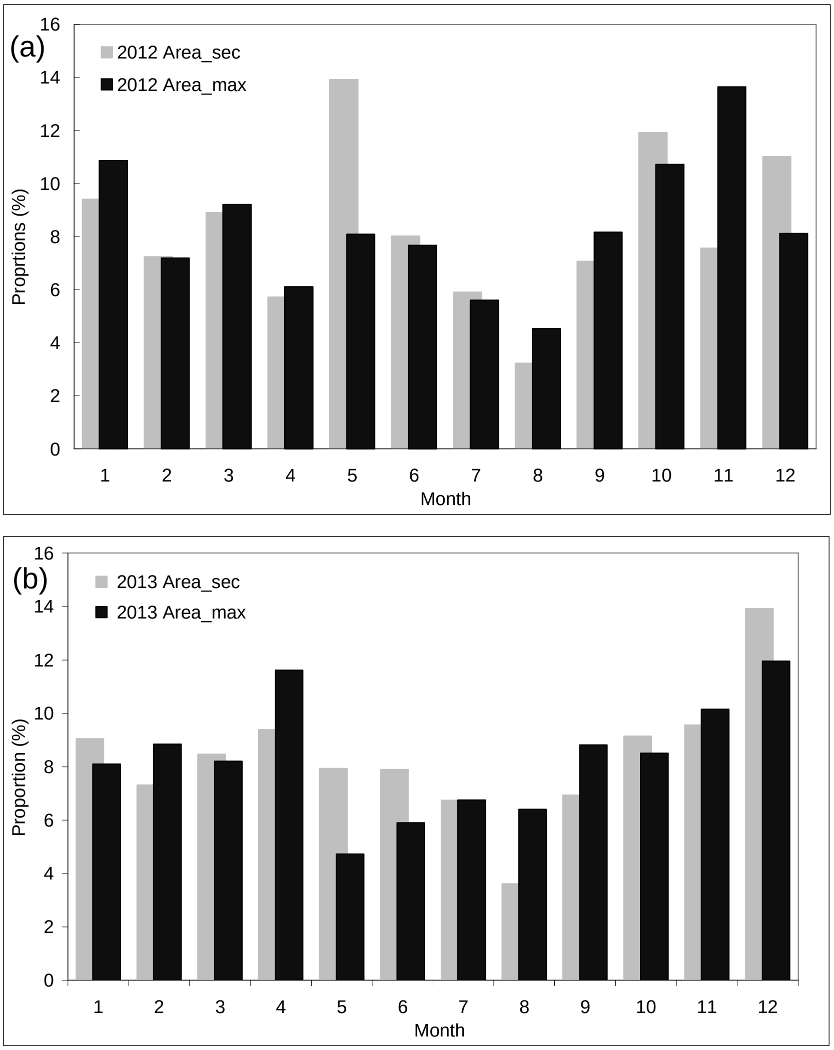

Figure 6. Monthly proportions of flashes detected by WWLLN in Area_max and Area_sec: (a) in 2012 and (b) in 2013.