Response to Anonymous Referee #1

Review for NHESS-2017-105

Title: Comparison of lightning activity in the two 1 most active areas of the Congo Basin

Authors: Kigotsi et al.

General comments: This manuscript presents an exploratory analysis of lightning activity over two distinct areas of Congo Basin: 1) the area where the maximum annual lightning flash rate density (FRD) is observed (west of the mountains that delineate the Rift Valley), hereinafter called Area_max, and 2) the area just west of Area_max, where very high but less pronounced FRD is observed, hereinafter called Area_sec. The manuscript is of the interest to the audience of this journal but needs a few adjustments. I recommend its acceptance only after addressing the issues described below.

Response of the authors

The authors thank the reviewer for her/his careful work to evaluate the paper. We appreciate the comments and the remarks that help to improve the paper. The paper required a major revision and we hope to have made corrections enough to make the paper **clearer and more relevant paper.**

Substantial modifications are made, especially a figure is added to have a wider view of the data and justify some choices. The study is systematically extended to 2012 data, to have a more robust comparison between both areas, which is the goal of the paper. We delete a figure and add a new graph and a new figure to show one case of distribution of a strong daily lightning activity. We add information about the WWLLN data and network.

The interpretation is developed when possible. For example we now highlight an interpretation for the difference between both areas by using the paper by Jackson about MCS location over equatorial Africa: both areas (Area-max and Area_sec) are included in one of the four maximums described in Jackson et al.. They explain this large maximum is due to the AEJ-S, while two other maximums were explained by the orography and another by the Lake Victoria. We distinguish two maximums in this large maximum, from which Area_max combines the presence of AEJ-S with local orography and Lake Kivu.

We make most of the corrections suggested by the reviewers and we answer to the comments in the following.

Major remarks:

Data: a) Soula et al. (2016) did an excellent job in calculating WWLLN detection efficiency (DE) for each year (2005-2013). This work should leverage from Soula's work and correct 2012 (DE=4.44%) and 2013 (DE=5.90%) data before doing the analysis. The subtle differences from 2012 to 2012 shown here could be an artifact of the different DE.

First of all, we have to say the comparison is made between two areas with a large flash rate density (FRD) in Congo Basin and not from one year to the next.

These areas (Area_max and Area_sec) correspond to the maximums pointed out in Soula et al. (2016) and as the reviewer noted it in a comment, to the areas surrounding most hotspots in Africa noted by Albrecht et al. (2016). Area_max includes 6 out of the 10 hotspots (1,2,3,5,8 and 10) found in Albrecht et al., while Area_sec includes 2 out of the 10 hotspots (6 and 7).

The DE is considered in Soula et al. (2016) and it was calculated relatively to the LIS data that cumulate cloud-to-ground and intracloud flashes. Thus, the DE values found in Soula et al. are low for the whole study area, 5.9% and 4.4% for 2013 and 2012, respectively. However, the DE can depend on the region since the study area in Soula et al. was very large (25° × 25°). Soula et al. (2016) have clearly highlighted the increase of DE between 2012 and 2013, the rate of which can be estimated at about 34%.

We noted also the DE was not constant in the whole study area considered in Soula et al. (2016). Thus, the values 4.44% and 5.90% are average values for the whole area. We consider now the specific values of DE for both areas Area_max and Area_sec. The new figure 1 is made to show different parameters for each area from 2005 to 2013:

- ***the lightning activity issued from LIS***
- ***the lightning activity issued from WWLLN***
- ***the DE estimation calculated according to the methodology presented in Soula et al.***

We see DE was stronger in Area_sec from 2005 to 2009 and in Area_max from 2010 to 2013. The question to correct the data by applying DE can be asked. We choose to let the data without any corrections for several reasons:

- ***the correction can be applied only globally for a given area, it does not change the comparison of the parameters we compare between both areas when we use proportions (proportion of lightning versus month)***
- ***the DE is calculated for one year and for a given area. To take into account an eventual correction we have to add flashes uniformly in each month, in each 1-hour time interval, in each day… It seems too artificial to correct all flash numbers at such small scales as 1-hour window, day, month…***
- ***The correction could be made at the scale of the year for the number of flashes.***

b) Also, why is it relevant to compare 2013 to 2012? Also, was there something different in terms of atmospheric conditions (such as significant droughts, rainier year, El Nino, La Nina, etc.)? My suggestion is to make it simple and combine the years, you may be inserting a lot of uncertainties in your analysis.

Figure 1 can be a response to the comment because it provides an overview of LIS and WWLLN data over the 9-year period. The two years 2012 and 2013 are selected because they correspond to the strongest detection efficiency (DE) from the years we have in our database.

In Soula et al. (2016) the LIS data were used to compare the activity from one year to the next. The difference for the whole region was low since the maximum was found in 2009 (195,316 flashes detected) and the minimum was found in 2012 (182,560 flashes detected), which provides a difference of 6.5%. Considering 2013, LIS data provides 192,443 flashes detected which represents an increase of about 5% from 2012. The interannual variability was found low by considering LIS data. Now we consider for this work of comparison the DE at the scale of each area (Area-max and Area_sec) and the LIS data at each area too. The new information allows better describing the WWLLN data used in this study.

Session 3.3: c) I really don’t think that the analysis of number of days within classes of flash counts is considered an “Annual variability”.

Done, we use now Day-to-day variability

d) Also, why use only 2013?

We use 2012 and 2013 for a study more robust.

e) L146-147: “The number of days without any flash (CL0) is much larger for Area_sec than for Area_max (7 and 0, respectively).”. A difference of only 7 days is not representative of annual variability.

We change the first class because we now think it is not necessary to separate days without any flash and days with very low flash numbers (some cases have less than 10 flashes). Thus we consider now a first class corresponding to a very low flash rate (< 100 flashes per day in an area).

Session 3.4:

f) In essence, Fig.3 and Fig. 4 show the same results. Also, the results presented are really confusing making me not to get the relevance of this session.

Section 3.4 is deleted.

Session 3.5:

g) Did your really expect a correlation between daily number of flashes in each area? This is a very weak way to show that thunderstorms are different within each area and you should rethink how to approach this issue.

We explain at the beginning the approach that consist in comparing the lightning activity day by day. It allows us to show the strong lightning activity is often local, even if the conditions favourable for storm developments are present in larger areas. Figure 7 shows an example of daily lightning flash rate density.

Session 3.6:

h) Very confusing: : : first of all, “monthly proportions” to what? To total number of lightning in each year? If the objective is to show “monthly activity”, why not show flash counts by months? Or is it also the objective to show seasonal contrasts? Please explain better.

The section aims to present the annual distribution of the lightning activity, at the scale of the month. We call it now “Month-to-month variability”. We add a figure to show the annual cycle at the scale of the season defined by DJF, MAM, JJA and SON, as in Christian et al. (2003).

i) Again, what is the relevance of comparing 2012 to 2013?

We do not compare 2012 to 2013, the reason for considering two years is to have a more robust comparison between two areas.

Minor remarks:

In general, review the significant figures (or digits) of all your numbers.

E.g.: - L 99: ratios of 1.941 and 2.585, shoulb have only one significant digit –

We agree and correct. Two digits after dot are fine. 0.01 over 1 is about 1%.

L 106: 15.33 flashes km-2 <yr-1>, should have no significant digit after “point”, while 8.22 and 8.62 should be 8.2 and 8.6 (considering that lightning strokes are a single unit)

For the values around 8 for the flash density, effectively one digit after dot seems enough because 0.02 over 8 is about 0.25%. Consequently, one digit for 15.33 seems also enough, it would be 15.3.

L 9-23: Avoid using abbreviations in the Abstract text, such as Area_max and Area_Sec, except if explicitly explained in the Abstract.

At the beginning of abstract (first sentence), Area_max and Area_sec are explained.

L 28-29: As a reference, Albrecht et al. (2016) show the impact of resolution (0.1o, 0.25o, 0.5o) while ranking the lightning hotspots. Please see Table ES4 of supplemental material: https://doi.org/10.1175/BAMS-D-14-00193.2.

Thank you for this comment about the very instructive table. The initial comment we made in the paper was essentially related to the shape of the maximum area in the Congo basin. We note the reference to illustrate the effect of the spatial resolution on the maximum value of FRD and on its location and we develop the comments related to this aspect.

L 50-52: Table ES4 of supplemental material (https://doi.org/10.1175/BAMS-D-14-00193.2) also shows the persistence of DRC as the second Earth’s lightning hotspot.

The response in the previous point includes the response to this comment.

L 69-88: Please, make it clear that WWLLN detects only cloud-to-ground (CG) lightning and that it does not detect intracloud (IC) lightning, which, in general, is the majority of lightning produced by a thunderstorm. This is also one of the reasons why your values in Fig. 1a differ from those of Albrecht et al. (2016).

We do not compare the values of the FRD in our paper with those in Albrecht et al. (2016) since they are not comparable. However, according to several references the WWLLN can detect IC flash strokes but with a lower detection efficiency. The system

does not exclude the IC strokes, which could be made probably with a recognition of form.

For example, Rodgers et al. (2005) say :" The detection efficiency of the WWLL is also considered. In the selected region the WWLL detected _13% of the total lightning, suggesting a 26% CG detection efficiency and a 10% IC detection efficiency."

Abarca et al. (2011) says: "The network detects CG and intracloud (IC) flashes with the same efficiency as long as they have the same current magnitude and channel length (Lay et al. 2004; Rodger et al. 2005, 2006; Jacobson et al. 2006); however, CG DE is about twice the IC DE (Abarca et al. 2010) because CG flashes tend to have higher peak currents."

We note the WWLLN is less efficient for IC flash detection.

Abarca, S.F., Corbosiero, K.L., Vollaro D., 2011. The World Wide Lightning Location Network and convective activity in tropical cyclones. Mon. Weather Rev. 139, 175–191.

Rodger, C.J., Brundell, J.B., Dowden, R.L., 2005. Location accuracy of long distance VLF lightning location network: post algorithm upgrade. Ann. Geophys. 23, 277–290.

L 91, Figure 1: Although your analysis considers full years, the most adequate unit is "flash km-2 yr-1", and it should be called "flash rate density".

Done

L 93: ": : : days of year with thunderstorm activity: : :". Since WWLLN detects CG lightning only, you should substitute "thunderstorm activity" by "lightning activity".

The WWLLN detects also IC flashes, so thunderstorm activity can be used but lightning activity can be well adapted.

L 98-99: "On the contrary, the flash <rate> density <in an individual 0.05o resolution point> is very different : : :." . Is that correct?

We compare the ratio between the maxima flash (rate) densities in both areas, calculated in 2012 and in 2013 (Table 1). The ratio for one year can be different in one year and in the other.

L 104-105: "By comparing with the values reported by Soula et al. (2016) for a resolution of 0.1_, : : :" which are???

The sentence that follows in the text gives these values. Maybe we are not clear, we try to improve it.

L 115-116: Please give scientific references for this affirmation, or you should state that this is a speculative affirmation.

It was noted in Soula et al. (2016). We note the number of flashes per stormy day is larger in the region of the main maximum. To have more flashes during a day of storm, there are three possible explanations: more storms, storms more active, storms more stationary. It can be also a combination of several of the three explanations.

L 127: “Both areas exhibit the same type of <diurnal lightning activity> evolution with a large: : :”

Done

L130: Please annotate that Local Standard Time (or Solar Time) is the same as UTC (i.e., LST = UTC -0)

We note this sentence at the beginning of the section: “The time is indicated in UTC, which is two hours late compared to Local Time (LT = UTC + 2).” Be careful, the local time is different in western DRC and eastern DRC and local time is different from solar time that needs a calculation. Local time is the time used in the eastern part of the country (DRC) including both areas (Area_sec and Area_max).

L 137-154: You should show only Figure 3 or Table 2, they are redundant. The same is valid for Figure 4 and Table 3.

Tables are rearranged. Table 3 is deleted and the new table 2 includes now 2012 and 2013 data. Figure 4 is deleted and the new figure 4 includes 2012 (a) and 2013 (b). The table provides the number of days for each class and the percentage of the total number of days. The figure has its usefulness for the tendency of the evolution in each area and their comparison.

L160-161: Please define the specific day (or months) regarding the 179 and 92 days span.

Deleted

L 189-190: “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.”. This may be due to the contribution of nocturnal lightning by MCSs or isolated storms that develop later in the afternoon if compared to Area_max. If you take a closer look in Albrecht et al. (2016) Figure 3, you will see that there is more lightning during the night for the hotspots that are in Area_sec (i.e., 6th and 7th Africa's hotspots).

Good point. We add this comment: "This may be due to the contribution of nocturnal lightning by MCSs or isolated storms that develop later in the afternoon if compared to Area_max. Indeed, the work by Albrecht et al. (2016) shows in their Figure 3 that during the night, the hotspots located in Area_sec (i.e, 6th and 7th Africa's hotspots) exhibit a larger contribution to the daily lightning activity.

L 219: ": : : different locations of our areas". Not really. The daily cycles shown in Albrecht et al. (2016) consider a 1 degree box around the hotspots, and 6 out of 10 Africa's hotspots are within your Area_max and 2 hotspots (Africa's 6th and 7th positions) are within your Area_sec (vide Albrecht's Figs. 2 and 3).

We agree and the sentence did not express correctly what we wanted to say. We say now : "for several hotspots located in our areas"

L 219-220: "They found also a more pronounced daily cycle: : :". This is because they considered a smaller area (a 1 degree box around the hotspots).

We change the sentence to say our results are consistent with those from Albrecht et al.

Tables 2 and 3: "Number of days", plural in the first line of the tables.

Done

Table 3: explain what (%) means, i.e., proportion to what? The sum of % Is 100% in each column?

Deleted

Figure 4: Explain "proportaion of day"

Figure 4 is deleted but the proportion is still used. We now explain the proportion of days in the caption of the new figure 4 and in the caption of Table 2.

Response to the Review of "Comparison of lightning activity in the two most active areas of the Congo Basin" by J.K. Kigotsi, S. Soula and J.-F. Georgis

This paper takes a look at lightning activity in the "Dark Continent" that also happens to be (often) the leading contributor to global lightning. Accordingly, shedding light on the darkness is a valuable endeavor, and eventually this paper deserves to be published. The most important single need is to identify up front the reasons for the analyses selected, and then to make more detailed physical interpretation of what emerges from the analysis. Several additional areas are identified where improvements can be made below. These substantive issues are followed by detailed comments on the text.

Summary: Consider for publication after major revision

Response of the authors

The authors thank Earle Williams for his detailed and useful work to evaluate the paper. We appreciate the comments and the remarks that help to improve the paper. The paper required a major revision and we hope to make corrections enough to obtain a clearer and more relevant paper.

Substantial modifications are made, especially a figure is added to have a wider and more precise view of the data and justify some choices. We add information about the WWLLN data and network. The study is also extended to 2012 data, to have more robust results from the comparison between both areas, which is the goal of the paper. We delete a figure and add a new graph and a new figure to show one case of lightning distribution during a strong daily lightning activity. The interpretation is developed when possible. For example we now highlight an interpretation for the difference between both areas by using the paper by Jackson about MCS location over equatorial Africa: both areas (Area-max and Area_sec) are included in one of the four maximums described in Jackson et al.. They explain this large maximum is due to the AEJ-S, while two other maximums were explained by the orography and another by the Lake Victoria. We distinguish two maximums in this large maximum, from which Area_max combines the presence of AEJ-S with local orography and Lake Kivu.

We make most of the corrections suggested by the reviewers and we answer to the comments in the following.

Substantive Issues:

(1) WWLLN documentation

The WWLLN information is the mainstay of this study. Accordingly, more details about WWLLN are needed in the context of the two years selected for study. If differences are documented in selected parameters (Table 1), one would like to know how much of the differenced comes from the detection system and how much is real interannual variability. (That influences the physical interpretation.) So information on the number of receiving stations operating in both years during the period of interest would be helpful. It is widely believed that Africa is generally in third place in the ranking of tropical lightning "chimneys" and that is simply because WWLLN has rather few receiving stations in that part of the world. (In contrast, the other global VLF network, GLD360, is getting Africa much more prominently, but unfortunately Vaisala keeps its information about station numbers and locations secret.) See additional info on this aspect in Williams and Mareev (Atmos. Res., 2009). And toward justifying the scale for gridding of the data, estimates of the accuracy of stroke location are also appropriate. A mention of "continuous increase in detection efficiency" appears in line 77 but without further details. In the Franklin Lecture on "Lightning and Climate" (2012, AGU website), Williams has addressed the problem of the changing detection efficiency in using WWLLN and GLD360 observations as a diagnostic for climate change.

Response of the authors:

First of all, we have to say the comparison is made between two areas with a large flash rate density (FRD) in the Congo basin. These areas (Area_max and Area_sec) correspond to the maximums pointed out in Soula et al. (2016) and to the areas surrounding the hotspots in Africa noted by Albrecht et al. (2016). Area_max includes 6 out of the 10 hotspots (1,2,3,5,8 and 10) found in Albrecht et al., while Area_sec includes 2 out of the 10 hotspots (6 and 7). The comparison is not made from one year to another. The two years 2012 and 2013 are selected because they correspond to the strongest detection efficiency (DE) from the years we have in our database. The DE is considered in Soula et al. (2016) and it was calculated relatively to the LIS data that cumulate cloud-to-ground and intracloud flashes. Thus, the DE values found in Soula et al. are low for the whole study area, 5.9% and 4.4% for 2013 and 2012, respectively. However, the DE can depend on the region since the study area in Soula et al. was very large (25° × 25°). It is difficult to have a report on the WWLLN status during these two years. Anyway, Soula et al. (2016) have

clearly highlighted the increase of DE between 2012 and 2013, the rate of which can be estimated at about 34%.

In Soula et al. (2016) the LIS data were used to compare the activity from one year to the next. The difference for the whole region was low since the maximum was found in 2009 (195,316 flashes detected) and the minimum was found in 2012 (182,560 flashes detected), which provides a difference of 6.5%. Considering 2013, LIS data provides 192,443 flashes detected which represents an increase of about 5% from 2012. The interannual variability was found low by considering LIS data. Now, for this comparison study, we consider the DE at the scale of each area (Area-max and Area_sec) and the LIS data are used in each area (see Figure 1 in the new version of the paper). The new information allows better describing the WWLLN data used in this study. A new graph in Figure 1 displays the annual count of lightning flashes from LIS and WWLLN for each area and during the whole data period (2005-2013), and the DE values calculated in each area with the method used by Soula et al. (2016). The years 2013 and 2012 have the larger values of DE, which can justify to take these two years of reference for the comparison between both Area_max and Area_sec.

(2) Surface temperature documentation

In other studies, tropical lightning activity has been shown to vary with surface air temperature, also related to CAPE (instability). D. Romps has also shown recently that tropical CAPE may be scaling with the Clausius-Clapeyron relationship, and so there one has a predicted temperature dependence of CAPE. The reviewer has already made inquiry with the second author about this thermodynamic aspect, but the same question is appropriate here. Are surface meteorological observations available at any location in the DRC and in particular for the two areas targeted in this study? That would be a most welcome addition to the physical analysis and interpretation in this paper. The authors need to consider that virtually no additional information is provided about the surface conditions of the two areas they have selected for study.

Response of the authors:

It is difficult to find surface temperature data in the region considered in the study. Anyway, to use the temperature in the study requires the knowledge of its values in several locations of the areas and the consideration of the altitude. We look for differences of the

storm characteristics between two regions. The characteristics investigated are, the daily cycle, the distribution of the FRD, the annual cycle month by month and season by season, the distribution of the number of flashes produced during a day. The highlighting of differences has to be interpreted in physical concept with the available information.

(3) Expectations for seasonal variations

The semiannual variation of temperature, rainfall and lightning activity in the climatology of the Congo is well recognized (Christian et al., 2003; Williams and Satori, 2004) but is not mentioned in the interpretation of the Figure 6. In a single year of lightning observations with a detection system that is decidedly inefficient, the semiannual variation may not be so robust, but there are hints of this in Figure 6 already. For example, note the maxima in April in Figure 6b and the local maxima in Figure 6a for October. Also, since the two selected areas are displaced south of the equator, one expects to have an annual phase with maximum in NH winter, also consistent with Figure 6. Place what has been found for localized areas in the broader context of knowledge about Africa.

Response of the authors:

In Soula et al. (2016) the DE values for the WWLLN were already noted as low and discussed. First, we have to keep in mind the DE is calculated relatively to the LIS sensor that detects all flashes (intracloud and cloud-to-ground). Since the WWLLN detects principally the CG flashes (but also some IC flashes - see references added in the paper as Abarca et al., 2011 and Rodgers et al., 2005), the values of DE are obviously low. Thus, the DE values are indicative and what is interesting is to follow the DE values year after year. A major result found in Soula et al. is that according to the high flash rate within this region, a low proportion of flashes detected is representative of the climatology. It is true also in the present study.

Concerning the semiannual variability of the monthly rate, it has been found in Soula et al. it can be large at the scale of the Congo basin. Consequently, the variability is large for the restricted areas considered in the present study. It is of course arbitrary to consider month by month to analyze the semiannual variability of the lightning activity. It is also possible to consider the 3-month averaged flash proportion to smooth the effect of a specific month. The reference to choose the 3-month period is based on typical periods considered in other studies in the region (Christian et al., 2003; Jackson et al., 2009) and from Soula et al.

(2016) that made an average annual cycle from 9 years. Thus, the four periods are DJF, MAM, JJA and SON. We add this approach in the new figure 6 to point out the semiannual variation. It is now commented for a complete and continuous cycle of three years. We discuss the result for this figure in the context of the knowledge about Africa.

(4) Positive correlation between lightning areas

My understanding of developments in the Congo is that often convection in the elevated terrain on the eastern boundary develops cold outflows that then go out to the west to stimulate/initiate new convection there. This could be a basis for correlation. Ground conditions are cited, but better would be to cite antecedent rainfall conditions over a large domain that will influence the nature of the convection on subsequent days. I would also strongly recommend another correlation calculation with an area that is immediately adjacent to the primary area, as presently the two selected areas are separate. It would be helpful to show that you have greater correlation when an area immediately adjacent is analyzed.

Response of the authors:

This correlation study was made to check if the days with activity can correspond between two areas, in such a way that the conditions favorable for storms could affect both areas. We have chosen the areas because they correspond to the study. The result is a weak correlation. We have to keep in mind the correlation is evaluated between the daily numbers of flashes in each area. It is a quantitative correlation. After analyzing some case studies in this region, we can see the strong flash rate density is always very localized in a restricted zone, that is to say the strong activity is not extended. It can explain or help to understand the weak correlation between the flash numbers in each 5° × 5° area. At the scale of one day the large flash rate/density (and strong rainfall for example) is local. We explain that and we show an example of day with strong activity in both areas (Figure 7). It shows also that even if the areas are adjacent, the correlation can be weak.

Role of Lake Kivu

The lake effect is mentioned only briefly (lines 120 and 249) and may deserve some expansion. It is now known that Lake Victoria in Uganda (near to the region of interest) and Lake Maracaibo in Venezuela have dramatic effects on lightning activity. (See for example the recent work by Albrecht et al. on tropical lightning hot spots, already mentioned.) So more should be said about the physical role of this lake, with possible inclusion of information on its size and about other studies of that role.

Response of the authors:

We have discussed the possible effect of the lakes in Soula et al. (2016). We add some comments. We can use the figure 2 to show the effect of Lake Victoria, especially on the number of days. We can see a clear enhancement above the lake. This enhancement is less visible for the lightning flash rate density. It means the number of flashes per day of storm is lower than in other parts of the area. The storms are therefore frequent above the lake Victoria, but not very active in terms of lightning flash production.

(5) The MCS issue

In the last paragraph of the Discussion section, the contribution of mesoscale convective systems is invoked. My big problem with this suggestion is that the authors have already documented the traditional 4 pm maxima in the lightning activity, and that is strongly suggestive of local (solar-stimulated) convection (assisted by cold outflow boundaries) rather than MCS activity that generally maximizes later in the diurnal cycle (and hence the greater prevalence of sprites later in the diurnal cycle, about which the second author is well aware, plus the fact that Africa is the leading "chimney" for sprite activity globally according to ISUAL satellite observations). So I am inclined to agree with what is stated in line 279. But expanded discussion on this aspect is needed. The authors should also consult TRMM work by Karen Mohr on African convection. And given that Zipser et al. (2006) is invoked, the diurnal phase of superlative activity in that study should also be examined and reported here.

Response of the authors:

We agree with the reviewer that the reference Zipser has to be more commented. The work is supposed to point out differences between two areas and the diurnal cycle appears different in both areas. Since it is more pronounced in Area_max it indicates more activity issued from local conditions, what is said (presence of mountains, lake

Kivu). The influence of MCS can be more obvious when the daily cycle is less pronounced. Furthermore, Zipser et al. found larger proportion of intense convection in the region corresponding to Area_sec. We rewrite the end of the discussion by referring to the work made by Zipser et al. (2006), Jackson et al. (2009). We think the differences between both areas can be explained by considering Area_max combines two conditions favorable to thunderstorm development, the convergence associated to the AEJ-S (Jackson et al., 2009) and the local effect of orography and lake.

(6) Observations with little if any interpretation

The paper has many analyses and observations that are not accompanied by physical interpretation. The Abstract for example contains no physical interpretations at all. Table 3, Figures 3, 4 and 5 are in a similar category. This aspect needs major improvement. It is helpful if every proposed analysis has a specific scientific purpose, and so also warrants an interpretation.

Response of the authors:

An effort of development or addition of interpretation is made in abstract, discussion and conclusion. See the last sentence of the abstract.

Detailed comments/edits on the text:

The authors are not native English speakers and so there are many edits needed to clean up the text:

Line 18 Suggest dropping "very"

Done

Line 20 "days"

Done

Line 27 Suggest adding Williams and Satori (2004)

Done

Line 28 suggest changing "space" to "spatial"

Done

Line 30 change "instance" to "example"; delete "the"; "from the Lightning…"

Done

Line 31 “resolution”

Done

Page 2

Line 32 “larger dynamic”? Meaning?

Modified

Line 34 “maxima”

Done

Line 35 change “both” to “neither”

Done

Line 36 change to “maxima remains throughout the year in considering the lightning activity with 3-month seasons”

Done

Line 37 what is physical interpretation of “very sharp and localized maximum”

Done

Line 38 “in the eastern Democratic…”

Done

Line 42 “scattered over a large area”

Done

Line 43 “maximum activity could…”

Done

Line 43 “linear scale for flash density was…”

Done

Line 46 “maximum activity”

Done

Line 48 change “whole” to “entire”

Done

Line 49 “most of them quantified”

Done

Line 51 “maximum in flash density”

Done

Line 53 "The geographical extent of this region"

Done

Line 57 "high spatial resolution"; "allowed a better localization and specification of its shape"

Done

Line 62 "contrasting from year to year"

Done

Line 63 "extends roughly"

Done

Page 3

Line 66 "maximum activity"

Done

Line 70 change "dimension" to "area"

Done

Line 77 Attributable to what? (see earlier discussion).

Done

The paragraph is modified and developed.

Line 78 "the last two years"

Done

Line 81 "radiation"

DoneLine 84 delete the first "the"

Done

Line 85 quantify "very little attenuation"; it is not small and for this reason large numbers of sensors are needed for global surveillance

Done

Line 87 Why report this for 2014 when it is 2012 and 2013 that are used for analysis?

Done

line 91 This would be 5 km resolution. You should justify that in terms of the accuracy of the stroke location in Africa.

Done

line 94 "with the same"

Done

Page 4

Done

Line 95 “the flash count”

Done

Line 96 “the maximum flash density for both areas and for each year”

Done

Line 97 “exhibit total flash counts”

Done

Line 97-98 “indicates a stable situation from one year to the next. In contrast, the ratio…”

Done

Line 99 “one year to the next”   4 digits here is overkill on precision

Modified

Line 101 “localized”; “one year to the next”; “Furthermore, the spatial density…”

Done

Line 103 “depends on the spatial resolution”

Done

Line 104 “at a resolution”

Done

Line 105 “maximum of flash density”

Done

Line 109 “clearly appears”

Done

Line 114 “thunderstorms, which means that the number of flashes per day is larger…”

Done

Lines 115-116   These two factors could be distinguished with WWLLN observations but you need to check the temporal development.

Done

Line 117 I hope the authors disclose “specific and local conditions”

Done

Line 119   Which side and why?

Done

Line 120 “increases markedly”

Done

Line 124 “daily cycle of flashes detected by the WWLLN”

Done

Line 125 “These flash counts are calculated…”

Done

Line 126 “so that the flashes are associated with the …”

Done

Page 5

Line 129 “for the minima in the morning…”

Done

Line 130 “and for the maxima in the afternoon…”

Done

Line 131 “contrast in flash counts between…”

Done

Line 134 Add comma after “day”

Done

Lines 133 to 136 What is your interpretation?

Done

Line 138 “distribution of flashes”

Done

Line 139 “year of reference”? Only one year?

Done

Line 142 How were the various classes selected?

Done

Line 145 “also plotted in Figure 3”   (reduce redundancy)

Done

Line 148 “number of days”; “about twice that of Area…”; “157 versus 84”

Done

Line 155 “Variability of flash counts during…”

Done

Line 157 “a clear minimum activity”

Done

Page 6

Line 160 “defined as the high activity” But you haven’t quantified HAP and LAP.

HAP and LAP are not considered anymore

Line 165 change to “and also in roughly the same proportion…”

Deleted paragraph

Line 166 “with number of flashes exceeding 5000 (CL6-CL111)”

Deleted paragraph

Line 167 “during the LAP”

Deleted paragraph

Line 169 “during the HAP and the LAP”

Deleted paragraph

Line 170 “During the HAP”

Deleted paragraph

Line 171 “of days” ***Deleted paragraph***

Line 172 “number less than 5000”; “whereas during the LAP”

Deleted paragraph

Line 174 You don’t have a real motivation here. Tell why you might expect correlated behavior.

Done

Line 178 For this you should be giving local times, not UT times. Otherwise you lose the physical interpretation.

The local time and UT time correspondence is given at section 3.2. The difference is 2 hours for this region of Africa. The local time is not always relevant. For example in Europe we have the same local time en western France and eastern Poland… The sun time is completely different within these two regions of Europe (27° of difference of longitude that is to say 1.8 hour!)

Line 180 You should be reporting correlation coefficients in the text in the same form as in the figures. Otherwise this is potentially confusing.

Done

Line 182 “it also increases for the other”; “first glance” of what?

The expression "at first glance" is used to express both distributions are similar after looking rapidly.

Line 190 "is more wide

Done

Line 192 I don't understand the meaning here? Clear-cut?

Changed

Page 7

Line 193 Shouldn't this section be merged with 3.3 Annual variability. It is the same topic.

The title is modified and the section is extended. Section 3.3 is different, it is an analysis day by day.

No discussion of the important semiannual variation in this section.

Now it is made with comments on the new graph (Figure 6c) for 2-year evolution.

Line 194 "proportion"

done

Line 206 suggest adding text: "based on satellite optical observations of lightning" to distinguish from the approach taken here with VLF data. You should also define "hotspot"

It is expressed like that in Albrecht et al. and not defined, so it is supposed to be understood. Maybe we can add a comment about their technique, to eliminate a 100-km in radius area around a hotspot already reported. Thus, two hotspots have at least 100 km of distance between them.

Lines 210-211 What did A. Laing say in there about MCSs?

Line 214 Considered by whom? These are not the times considered in Section 3.2.

Made. It is modified for the times because we have to consider

Line 216 This is yet another time interval.

More commented now.

Line 217 This is not what you reported in lines 128-130.

More details are given

Line 219 "locations than our two areas"

Line 224 “result for 2011” on WWLLN ? Please clarify.

Now 2011 is included to show two complete annual cycles.

Page 8

Line 225 What is the meaning of “minimum proportion”?

Lowest value of the proportion. It is clarified.

Line 228 The authors need to articulate their views on the ITCZ in the lightning context. In my experience, the activity lightning is usually adjacent to the ITCZ because one needs subsidence to eliminate the widespread cloudiness that is shuts off the destabilizing influence of sunlight.

236-240 Nothing is included in here about antecedent conditions of rainfall, that can influence the Bowen ratio. See also Williams and Stanfill (2002; Comptes Rendues).

Line 249 Need more discussion on the role of “great lakes” in the lightning context

Line 250 “for the development”

Line 251 “at the planetary scale”; when do “the most intense storms” max out in the diurnal cycle? Are they isolated, or are they parts of MCSs?

Line 256 “spread from the east to the western Congo basin”

Done

Line 257 Only if MCS status. But don’t forget role of cold outflow toward the west.

Page 9

Line 259 And antecedent rainfall. In any case, more should be said about the nature of the surface in the areas selected. In this context, Williams and Satori (2004) should be consulted.

Done

Line 263 “regions of strong coupling between the atmosphere…”

Done

Lines 264-265 One does not want a contrast if one is seeking to explain correlated behavior.

Done

Line 266 “mesoscale convective systems”

Done

Line 269 “in the Congo basin”

Done

Line 270 “frequently overshoots the tropopause. The climatology…”

Done

Line 272 “From a five-year series of data…”

Done

Line 273 “to the western side of the high mountains”

Done

Line 275 “maxima in the number”

Done

Line 279   I tend to agree with this statement but the discussion on MCSs needs to be elaborated on here.

Conclusions, like Abstract, is lacking in physical interpretation.

Line 282 “The spatial and temporal characteristics of the lightning…”

Done

Line 282 “strongest thunderstorm activity”

Done

Line 283-284 change to “with a secondary maximum”; “concentrated in the same part”

Done

Line 287 to 288 “is similar in both areas

Done

References

Suggest adding Williams and Satori (2004)

Williams et al. (2000, JAM) considers variations of tropical flash rates and diurnal cycles of flash rates and storm counts.

Williams (2012, Franklin Lecture) considers impact of changes in WWLLN detection efficiency over time.

Table 1   Two significant figures is probably more appropriate.   In some places the authors use four!

A figure is given to show the flash number in each area over the 9-year period 2005-2013. The DE values are also provided.

Figure 1   The hotspot areas straddle the equator. Some discussion is needed about that aspect alone in driving the lightning counts up high.   These zones are visited at least twice per year by the zone of instability. Caption could also mention location accuracy of individual strokes.

Figure 2 Suggest changing “amounts” to “counts”   Please compare this variation with those documented in Williams et al. (JAM, 2000).   4 pm is very consistent, and with Schumann resonance observations of “background”

Done.

Figure 4 Better to show flash counts that CLi classes, which require going elsewhere to check on definition/motivation.   What is the thermodynamic situation on days with > CL10? Curious minds want to know.

The class is an interval of flash number. The purpose is to compare both areas and with this choice of class width, the difference is shown. We could consider more classes, but the number of flashes is displayed in Figure 5 anyway.

Figure 5 If R^2 value are used here, same values should be discussed in the text.

Done

Figure 6   Need more discussion on semiannual and annual variations in general. (See earlier remarks.)

Done

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

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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) of the Congo basin is made with data obtained by the World Wide Lightning Location Network (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 rate density (FRD) with maximums in a ratio of 1.94 and 2.59 for 2012 and 2013, respectively. The FRD is much more widely distributed in Area_sec, which means the whole area contributes more or less equal to the lightning activity. 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 proportion of days with ~~very~~ low lightning rate (0-1,000 flashes per day) is much larger (~45% in 2013) compared to Area_max (~23% in 2013). In Area_max the proportion of days with moderate lightning rate (1,001-6,000 flashes per day) ~~decreases more slowly and~~ is larger (~68.5% in 2013) compared to Area_sec (~46% in 2013). The very intense convective events are slightly more numerous in Area_sec. ~~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 (annually and daily), in intensity and in location. Area_max combines two favourable effects for thunderstorm development, the convergence associated with the African easterly jet of the Southern Hemisphere (AEJ-S) and a geographic effect due to the orography and the presence of a lake. The location of the strong convection in Area_sec is modulated by the distance of westward propagation/regeneration of MCSs in relation with the phase of Kelvin waves.

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; Williams and Sátori (2004), Albrecht et al., 2011, 2016, Cecil et al., 2014, Soula et al., 2016). Actually, the features of the maximum area depend on the spatial resolution considered in the calculation of the flash rate density (FRD) and the scale resolution in the graphic representation. Albrecht et al. (2016) performed a very detailed analysis of FRD thanks to Lightning Imaging Sensor (LIS) data around the Earth, by using several spatial resolutions. They showed the features of the maxima FRD strongly depend on the spatial resolution and on the duration of the period considered for the study. Thus, the location and the value of the first- and second-ranked maxima FRD stabilize when the period is longer. With the better resolution (0.1°) used in Albrecht et al. (2016), the second-ranked hotspot is always located around [28°E; 2°S] from five years of data. Furthermore, they showed most of the first ten lightning hotspots over the ~~whole~~ entire African continent, including the strongest ones, are located in Democratic Republic of Congo (DRC). By considering the maps of FRD in Albrecht et al. (2016), the existence of two regions of maximum activity in DRC is displayed but the non linear scale does not allow a quantitative comparison of the maximum values.

Cecil et al. (2014) provided two maps of ~~the~~ lightning flash density from the Lightning Imaging Sensor (LIS) and Optical Transient Detector (OTD) data with different resolution, 0.5° and 2.5° and a non linear 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 maxima 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~~ neither maxima remain throughout the year in considering the lightning activity with 3-month seasons ~~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~~ pronounced maximum in the annual and seasonal lightning flash density in the 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~~ over a large area. In this study the region of maximum activity could be analyzed in detail because the linear scale for flash 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 activity 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 entire African continent and they showed most of them quantified, including the strongest ones, are located in DRC.~~

The results of Soula et al. (2016) provided the following characteristics. The main maximum in lightning 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 geographical extent 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 spatial resolution and the linear scale used in Soula et al. (2016) allowed a better localization and specification of 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 contrasting from year to year during the period of the study. It extends roughly 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 activity. 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 area ~~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 for the present study. The WWLLN (www.wwlln.net/) is a global lightning detection network around the Earth. The electromagnetic radiation emitted by lightning strokes (from cloud-to-ground and intracloud flashes) at very low frequency (VLF) and called sferics are detected by the sensors of the WWLLN (Abarca et al., 2011). 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 order to give an idea of the growth of the number of WWLLN stations spread on the planet, it was 11 in 2003, then 23 in 2005, 30 in 2007 and 67 in 2013, according to the report made by Rodger et al. (2014). According to Indeed, the changes in the network during this 9-year period (2003-2013) can explain the continuous increase of the detection efficiency (DE) from 2005 to 2013 observed by Soula et al. (2016) in the total domain of the study. According to Abarca et al. (2011), DE for CG flashes is about twice that for IC flashes.

We analyze the DE evolution during this period for each area. For this purpose and in the same way as Soula et al. (2016) for the whole Congo basin area, Figure 1 displays the annual numbers of lightning flashes detected by WWLLN and LIS in Area-max and Area_sec during the period 2005-2013. In the same graph, the values of the WWLLN DE relative to the LIS data, are reported for each area. DE is calculated by following the methodology developed by Soula et al. (2016), i.e. by applying the correction coefficient for the estimation of the number of the whole lightning flashes LIS could detect with a continuous survey. First, the number of flashes detected by LIS in each area does not vary much during the period, it is always larger in Area_max, its minimum is observed for 2007 in each area and more pronounced for Area_sec, and the maximum is observed for 2005 in each area too. Thus, no increase tendency is observed in each area. Secondly, the number of flashes detected by WWLLN in each area increases after 2008, especially during the last two years 2012 and 2013. As a consequence, DE is significantly larger for 2012 and 2013, and reaches 4.96% and 7.50% in Area_max, respectively, and 4.24% and 6.11% in Area_sec. This increase of DE is completely independent of the number of flashes detected by LIS that is relatively stable during the last years, which means it is totally related to the WWLLN performance.

According to the DE values, we select the last two years of the period (2012 and 2013) for a comparison of the characteristics of the lightning activity in Area_max and Area_sec.

3 Results

3.1 Spatial distribution of the lightning activity

Figure 2a-b shows the annual FRD, in flash km^{-2} yr^{-1}, calculated with a resolution of 0.05° from WWLLN data in the large domain of the Congo basin for 2012 and 2013, respectively. Figure 2c-d shows the number of days of the year with ~~thunderstorm~~ lightning activity in the same domain with the same resolution for 2012 and 2013, respectively. The white frames indicate the two areas with strong activity (left Area_sec and right Area_max). Table 1 displays the flash count, the maximum FRD for both areas and for each year. Both areas of same size (5° × 5°) exhibit total flash counts in a ratio of about 1.32 for both years, which indicates a ~~almost~~ stable situation from one year to the next. On the contrary, the ratio of the maximum FRD is very different from one year to the next, since it is 1.94 and 2.59 for 2012 and 2013, respectively. This difference can be easily understood since the maximum value is very localized and can change substantially from one year to the next, and furthermore the spatial density resolution used in the study is very high, with a value of 0.05°. The maximum value of the density depends on the spatial resolution, in the sense that it increases when the resolution becomes higher. By comparing with the values reported by Soula et al. (2016) at a resolution of 0.1°, it is clear that the maximum of the annual FRD is larger for 0.05°. Indeed, it is 12.86 fl km^{-2} yr^{-1} at 0.1° and 15.33 fl km^{-2} yr^{-1} at 0.05° in 2013, and it is 8.22 fl km^{-2} yr^{-1} at 0.1° and 8.62 fl km^{-2} yr^{-1} at 0.05° in 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. This observation is consistent since a day is stormy when at least one flash is detected in the pixel.

The difference between the distributions in the two areas clearly appears regarding both lightning FRD and number of days of the year with lightning activity in Figure 2. 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~~ difference between both areas is stronger for FRD compared to the number of days with thunderstorms, which means that the number of flashes per stormy 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 (Soula et al., 2016). The differences observed in the maximum values and the distributions of the lightning FRD 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 the west side of which the FRD increases markedly, and the presence of the lake Kivu (29.2°E; 1.9°S) above which the FRD increases (Soula et al., 2016). No specific shape of the FRD or stormy day is visible in Area_sec.

3.2 Daily cycle

Figure 3 shows the daily cycle of ~~the amounts of~~ the flashes detected by the WWLLN in Area_max and Area_sec, for 2012 and 2013. The time is indicated in UTC, which is two hours late compared to Local Time (LT = UTC + 2). These flash counts are calculated over one hour and averaged over all days of the year. The time scale of the graph is made so that the flashes ~~amounts~~ are associated with the beginning of the 1-hour period of calculation. Both areas exhibit the same type of ~~evolution~~ diurnal lightning activity with a large proportion of flashes during the afternoon and whatever the year. The minimum and maximum numbers of flashes are observed roughly at the same time in both areas. The minimum is observed in the morning between 08:00 and 09:00 UTC for Area_max and between 07:00 and 08:00 UTC for Area_sec, for both years. The maximum is observed in the afternoon, between 16:00 and 17:00 UTC for Area_max and for both years and for Area_sec in 2013, and between 17:00 and 19:00 UTC for Area_sec in 2012. The contrast in flash counts between the morning minimum and the afternoon maximum is stronger for Area_max (ratio of 14.5 and 15.4, for 2012 and 2013, respectively) than for Area_sec (ratio of 6.2 and 4.7, for 2012 and 2013, respectively). It means the diurnal cycle is much more pronounced in Area_max. Consequently, while the lightning flash 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 Day-to-day variability

We compare the lightning activity in both areas in terms of daily distribution of ~~the~~ flashes detected during one year. The years of reference are 2012 and 2013 with a total of 366 and 362 days, respectively, 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 and each year, over 12 classes of flash number. This result is expressed in terms of number of days for each area and year, and in proportion

(%) of the total number of days for the year in each area. The incrementing of each class is done on 1,000 flashes, except for the class CL1 that is on 900 flashes from 101 to 1,000 flashes. The first class CL0 corresponds to 0-100 flashes to distinguish the days with a very low number of flashes. The last class CL11 groups the days with more than 10,000 flashes. ~~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 distribution is similar for both years, (a) for 2012 and (b) for 2013. The number of days ~~without any flash~~ in CL0 is much larger for Area_sec than for Area_max (59 and 7, respectively, in 2012, 43 and 4 in 2013), as indicated in Table 2. For CL1 corresponding to the flash numbers 101-1,000, the number of days is also larger for Area_sec, slightly in 2012 with 130 and 121 days, respectively, markedly in 2013 with 121 and 80 days, respectively. ~~about two times that of Area_max, 157 and versus 84, respectively~~. On the contrary, the number of days for classes corresponding to intermediate flash numbers (CL2 to CL4 in 2012, CL2 to CL6 in 2013) is significantly larger for Area_max, for both the cumulative number of days (202 against 144 in 2012 and 248 against 168 in 2013) and for each class considered separately. For the classes with a very high activity (CL5 to CL11 and CL7 to CL11, in 2012 and 2013, respectively, ~~than 6,000 flashes per day)~~ the total number of days is small and not very different in both areas (36 and 30 in 2012, 20 and 30 in 2013, for Area_max and Area_sec, respectively. ~~and class and even equal for the cumulative number of days (30 days).~~

From 2012 to 2013, for both areas, the proportion of the number of day decreases in the first three classes (CL0-CL2) and for the cumulative value it is ~62% in 2012 and ~45% in 2013 for Area_max, and ~70% in 2012 and ~61% in 2013 for Area_sec. It is almost equal in CL3: ~20% in 2012 and ~19% in 2013 for Area_max, and ~14% in 2012 and ~14% in 2013 for Area_sec. It increases almost in all classes after CL3 and for cumulative value it is ~18% in 2012 and ~36% in 2013 for Area_max, and ~16% in 2012 and ~25% in 2013 for Area_sec.

~~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 clear minimum 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 defined as the 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

Now we consider the lightning activity for a comparison day by day of both areas to perform a quantitative correlation. The goal is to evaluate if both areas are simultaneously concerned by the storm activity or if they are with a shifted time. In order to illustrate the result about this correlation 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 counts 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^2 is ~0.118 and in the second case it is ~0.064. 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 increases does for the other. At first glance, both distributions are similar. They reflect the trend highlighted by Figure 4 insofar as the low values (≤ 1000 flashes per day) are more numerous in Area_sec. Inversely, the intermediate values (between 1,001 and 5,000 flashes per day) are more numerous in Area_max with 230 days in 2013, against 156 days for Area_sec. For the values exceeding 10,000 flashes per day, there are 7 days for Area_max and 5 days for Area_sec in 2013 (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 widely distributed

~~spread~~ during the day in Area_sec as indicated in Figure 3. This may be due to the contribution of nocturnal lightning by mesoscale convective systems (MCSs) or isolated storms that develop later in the afternoon if compared to Area_max. Indeed, the work by Albrecht et al. (2016) shows in their Figure 3 that during the night, the hotspots located in Area_sec (i.e, 6th and 7th Africa's hotspots) exhibit a larger contribution to the daily lightning activity. Thus, by considering the day according the lightning activity (06h00-06h00), the episodes of strong lightning activity in this area are more likely to be counted in full. ~~less likely to be cut~~.

3.6 Month-to-month variability

Figure 6a-b shows the monthly proportion 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.

Figure 6c shows the 3-month proportion over a longer period including data from 2011. The 3-month periods are chosen according to Christian et al. (2003), Jackson et al. (2009), and Soula et al. (2016). Thus, the months of June, July and August are grouped in JJA, September, October and November in SON, December, January and February in DJF, and March, April and May in MAM. The annual variability at this 3-month scale is more visible and constant from one year to the next. Indeed, for both areas, the minimum is always in JJA with a constant decrease during the preceding 3-month periods. For the maximum, it seems SON is more favourable to Area_max while DJF is for Area_sec.

4 Discussion

Albrecht et al. (2016) studied the lightning hotspots over the Earth, based on satellite optical observations of lightning. They consider that a hotspot is a region 100-km in radius around a maximum of FRD. 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 FRD in Area_max.

The characteristics of the diurnal cycle observed in Area_max and Area_sec is 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. For two 1-hour intervals (14:00-15:00 UTC and 17:00-18:00 UTC) besides eight considered in their study, they found the location of a sharp maximum of the average hourly frequency of coldest clouds in eastern DRC close to Area_max. The intervals 15:00-16:00 and 16:00-17:00 UTC were not plotted in their graphs. They noted this maximum for the two months April and October analyzed in the study. They also showed that the thunderstorm activity is minimum in the part of DRC that corresponds to both areas of our study during the time interval 05:00-06:00 UTC in April and during 08:00-09:00 UTC in October (06:00 and 07:00 UTC were not plotted). The present observations about minimum and maximum lightning activities displayed in Figure 2 are consistent with those by Laing et al. (2011). Indeed, the maximum of the activity is invariably between 16:00 and 17:00 UTC for Area_max, and in a larger temporal window for Area_sec (~17:00-19:00 UTC in 2012 and 16:00-17:00 UTC in 2013). The maximum storm activity is therefore more variable in time for Area_sec. The minimum is invariably between 07:00 and 08:00 UTC for Area_sec, between 08:00 and 09:00 UTC for Area_max. In Albrecht et al. (2016) for the study of lightning hotspots, the daily cycles are considered for ~~different~~ several hotspots located in our areas. They found a daily cycle more pronounced for the hotspots included in Area_max compared to the hotspots included in Area_sec, which is consistent with the present study.

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. At the seasonal scale, the monthly activity is cumulated over three months following the average monthly activity found in Soula et al. (2016) for the whole Congo basin. The inter-annual variability is well visible and reproduced from one year to the next. ~~A~~

~~result for WWLLN data from 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. Figure 7 displays the daily density of lightning flashes detected by WWLLN on 25th of December 2013 in Area_sec (a) and in Area_max (b). This day is considered because the activity is strong in both areas with 18107 and 10257 flashes detected in Area_sec and Area_max, respectively. Firstly, this distribution shows the lightning density is high (scale in fl km^{-2} day^{-1}) in local spots that correspond to convective cores of thunderstorms. In other words, for a given day, the lightning activity can be strong in a restricted area and weak around in term of flash number. This characteristic of the storm activity is well known and pointed out by many works (Carey et al., 2005; Soula et al., 2014). Secondly, the lightning spots seem east-west elongated in majority, which could indicates a propagation of the storms within this direction. Thus, the strong activity of a given storm is probably limited over the time. However, the correlation between both areas probably exists because of ~~the most natural influence that could be assumed between the two areas would probably result from storms propagating from east to west.~~ the eastward 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 the east to the western Congo 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 strong coupling between the atmosphere and the 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~~ differences between lightning activities of the two areas.

Farnsworth et al. (2011) pointed out that the ~~mesoscale convective 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) and Zipser et al. (2006) (on deep convection in the Congo basin). They showed convection in the Congo basin frequently overshoots the tropopause. The climatology of MCSs in Equatorial Africa, including the whole Congo basin, was presented in Jackson et al. (2009). From a five-year 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 side of the high mountains of the Rift Valley is the most active in terms of storm activity because it includes two of four maxima in the number of MCSs that they have identified. In our study, Area_max and Area_sec coincide with the region where Jackson et al. (2009) found ~~one of~~ the ~~two~~ main number maximum of MCS. Actually, in Jackson et al., two cores appeared in the structure of this main maximum, one that corresponds to Area_sec with a less pronounced maximum of number of MCS and a larger number of lightning flashes per MCS. The second core in Jackson et al. corresponds to Area_max with a more pronounced maximum. They explain the origin of the large number of MCS in this large area by a maximum of midtropospheric convergence on the west side of the African easterly jet of the Southern Hemisphere (AEJ-S). They observe this condition more pronounced in SON season compared to MAM in the same way that we observe also more flashes according to Figure 6c. Indeed, according to Mohr and Thorncroft (2006) and Laing et al. (2008), the vertical shear related to the African easterly jet (AEJ) influences the location of intense convective systems. Furthermore, mountain ranges help to initiate long-lived MCSs (Laing et al., 2008; 2011). According to these authors, in all the regions the convection initiates over the elevated terrain and then propagates in conditions of moderate vertical shear to develop into mesoscale systems. On the other hand and according to several authors, the propagation of convection in Equatorial Africa is modulated by convectively coupled, equatorial Kelvin waves (Laing et al., 2011). During the active phase of these eastward-propagating large-scale waves, MCSs are larger and more intense. These convection systems occur farther east from day to day, and propagate westward within the Kelvin wave envelope. During the dry phase of the Kelvin waves an upper-level convergence is produced, which eliminates the deep convection and the westward propagation. Thus, the region corresponding to Area_max seems to have a stronger maximum of MCS number, as we find a larger FRD. Area_max combines two conditions favourable for thunderstorm activity, the convergence evoked by Jackson et al. (2009) for the large region and a local orographic effect that reinforces the effect of the first one. Area_sec seems to take advantage of the westward propagation/regeneration of MCS, at a distance from the initial occurrence that depends on the phase of the Kelvin waves, which explains the widespread large values of FRD observed within this area.

The presence of mountains or elevated terrain is always a determining factor in the mechanism of thunderstorm. For example at a very local scale, Munoz et al. (2016) explain the role of the topography combined with Nocturnal Low Level Jet in the largest FRD in the world observed in the region of the lake Maracaibo, Venezuela. At a more global scale, William and Sátori (2004) compared the lightning and rainfall activities in both Amazone and

Congo basins and interpret the greatest FRD observed in Congo basin in terms of features more continental (drier and warmer) and a larger elevation.

~~which means suggests a substantial proportion of lightning flashes are not produced by MCS in Area_max.~~ According to Zipser et al. (2006) the proportion of intense convective events is larger in the region corresponding to Area_sec compared to that corresponding to Area_max (see their figure 3). This result is consistent with the present figure 5 concerning the distribution of the daily flash number in each area, especially the graph (b) where the flash counts are made from 06:00 to 06:00 UTC. Furthermore, the DE is a little lower in Area_sec compared to Area_max, according to the results displayed in Figure 1. Thus, Area_sec is concerned by a more irregular thunderstorm activity, with both the least active days and the most active days. It is well illustrated with the example in Figure 7, displaying the daily lightning activity for the most active day in Area_sec (see Figure 5a). Indeed, the FRD for the day is more scattered in the whole area for Area_sec. The distribution of thunderstorm activity is substantially different in each area, concentrated with a very marked daily cycle in Area_max, and scattered with a daily cycle much less pronounced.

5 Conclusion

The spatial and temporal characteristics of the lightning activity are analysed in two areas of the Congo basin, Area_max with the strongest thunderstorm activity and Area_sec with a secondary maximum ~~lower one~~. First, the lightning flashes are much more concentrated in the same part of Area_max for both years, while they are ~~more scattered~~ widespread 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 similar 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. These differences are consistent because Area_max combines two favourable effects for thunderstorm development, the convergence associated with the AEJ-S, especially during SON and DJF, and a geographic effect due to the orography and the presence of a lake. The location of the strong convection in Area_sec is widespread, according to the distance and direction of propagation/regeneration of MCSs that initiate farther eastern, especially in relation with the phase of Kelvin waves.

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

	Flash count		Maximum flash density (fl yr^{-1} km^{-2})	
	2012	2013	2012	2013
Area_max	696,144	1,000,687	8.6	15.3
Area_sec	526,278	760,405	4.4	5.9
ratio	1.32	1.32	1.94	2.59

~~**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~~
~~1,001 – 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~~

Table 2. Number of days corresponding to lightning classes in the two study areas during the 2012 (366 days) and 2013 (362 days). The percentage is calculated in relation to the total number of days during the year.

Flash number	CLASS	Number of days (%)			
		2012		2013	
		Area_max	Area_sec	Area_max	Area_sec
0 – 100	CL0	7 (1.91)	59 (16.12)	4 (1.10)	43 (11.88)
101 – 1,000	CL1	121 (33.06)	130 (35.52)	80 (22.10)	121 (33.43)
1,001 – 2,000	CL2	99 (27.05)	68 (18.58)	79 (21.82)	58 (16.02)
2,001 – 3,000	CL3	73 (19.94)	52 (14.21)	70 (19.34)	52 (14.36)
3,001 – 4,000	CL4	30 (8.20)	24 (6.56)	43 (11.88)	29 (8.01)
4,001 – 5,000	CL5	16 (4.37)	17 (4.64)	38 (10.50)	17 (4.70)
5,001 – 6,000	CL6	10 (2.73)	7 (1.91)	18 (4.97)	12 (3.31)
6,001 – 7,000	CL7	4 (1.09)	4 (1.09)	12 (3.31)	11 (3.04)
7,001 – 8,000	CL8	2 (0.55)	1 (0.27)	7 (1.93)	10 (2.76)
8,001 – 9,000	CL9	4 (1.09)	1 (0.27)	2 (0.55)	2 (0.55)
9,001 – 10,000	CL10	0 (0.00)	0 (0.00)	2 (0.55)	2 (0.55)
> 10,000	CL11	0 (0.00)	0 (0.00)	7 (1.93)	5 (1.38)
Total		366 (100)	366 (100)	362 (100)	362 (100)

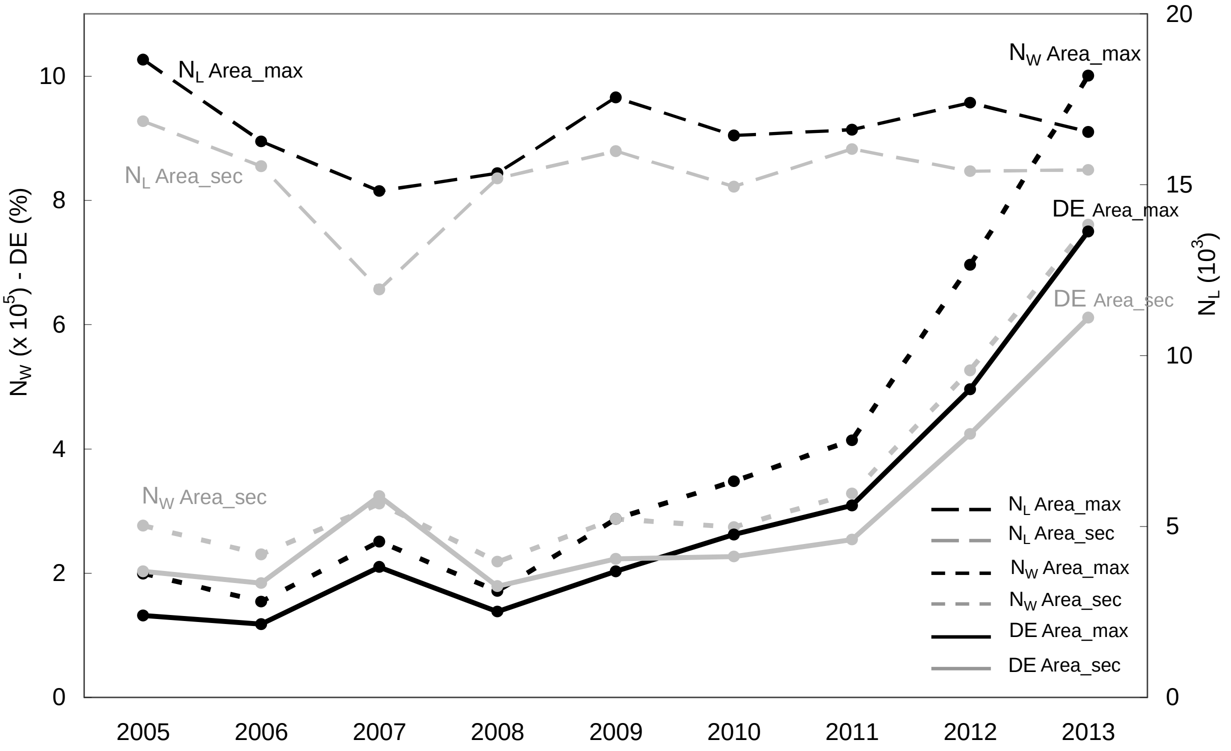

Figure 1. Annual number of flashes detected by the WWLLN (N_W) and that detected by LIS (N_L) for each area, and estimated detection efficiency (DE) for WWLLN data relative to LIS data, according to the methodology developed in Soula et al. (2016).

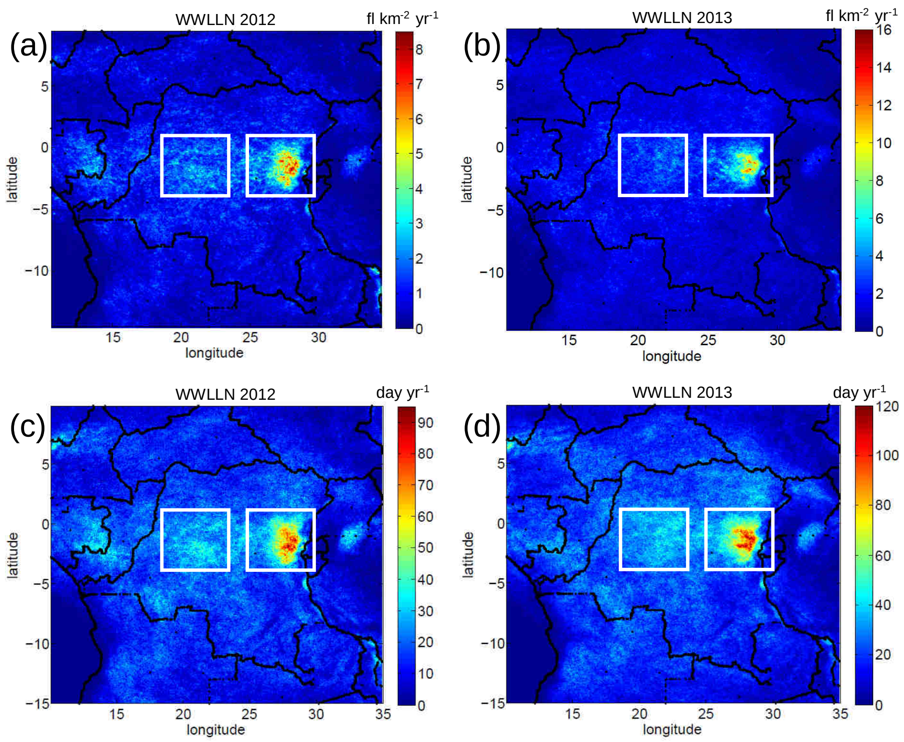

Figure 2. (a) and (b) Lightning density in fl km^{-2} yr^{-1} calculated at a resolution of 0.05° from WWLLN data in the area of Congo Basin for 2012 and 2013, respectively. (c) and (d) Number of days of the year with thunderstorm activity in the same area with a resolution of 0.05° for 2012 and 2013,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

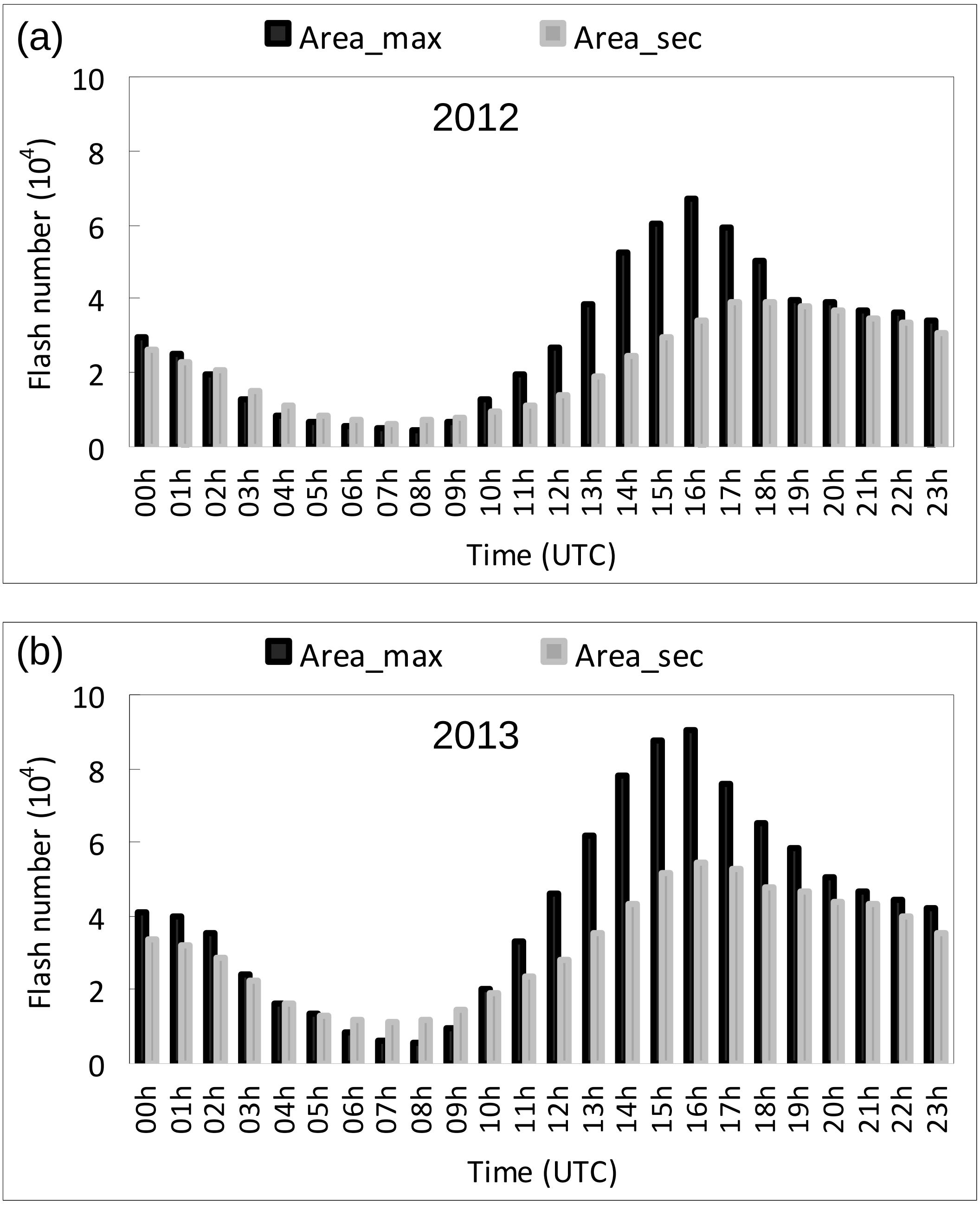

Figure 3. Daily evolution of the hourly lightning flash counts in Area_max and Area_sec for 2012 (a) and 2013 (b).

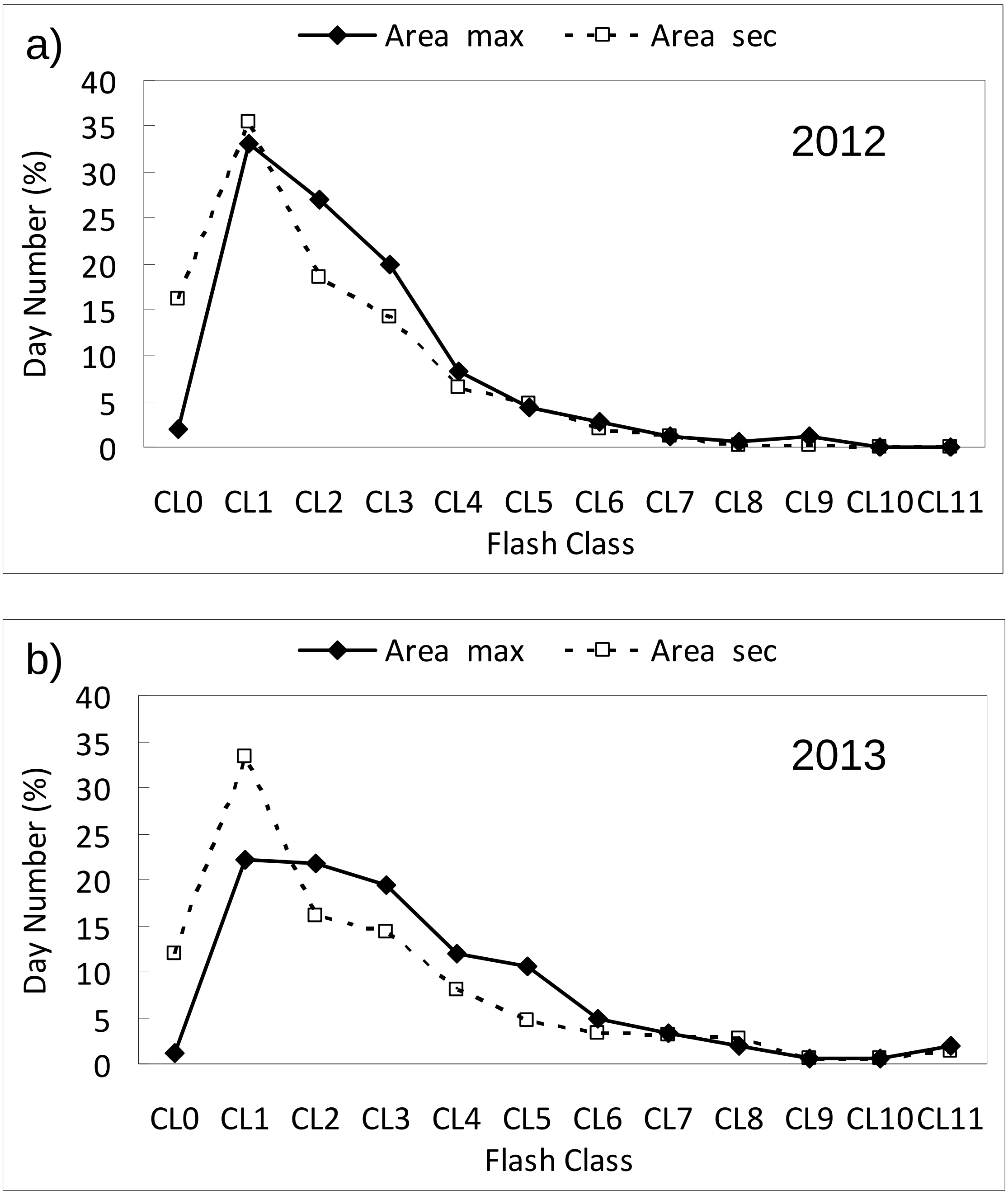

Figure 4. Distribution of the number of days (% of the annual number of days) versus the classes of flash number in both areas: (a) for 366 days in 2012, (b) for 362 days in 2013.

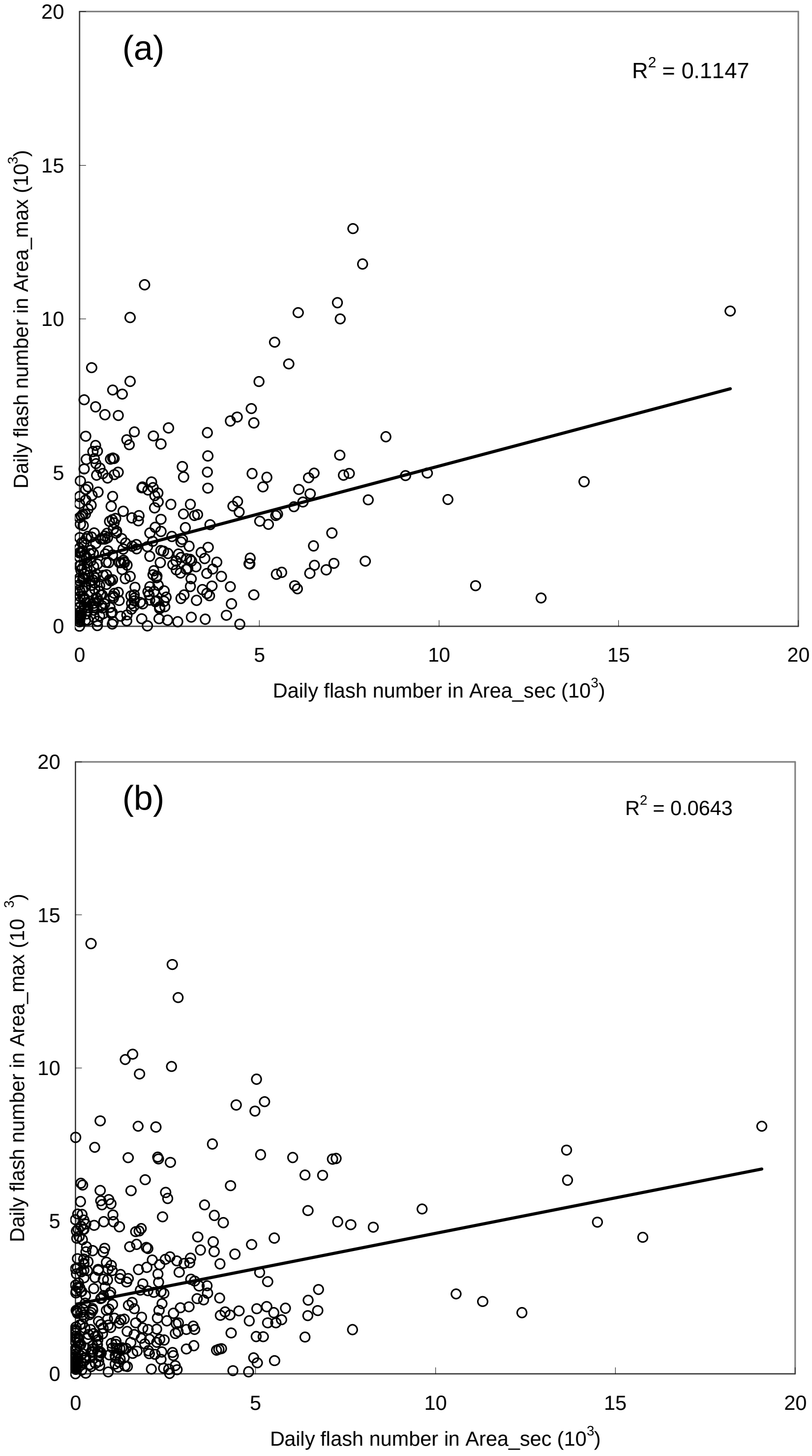

Figure 5. Diagrams of correlation between daily numbers of lightning flashes for Area_max and Area_sec in 2013: (a) at calendar daily scale (00h00-24h00 UTC) and (b) at lightning activity daily scale (06h00-06h00 UTC).

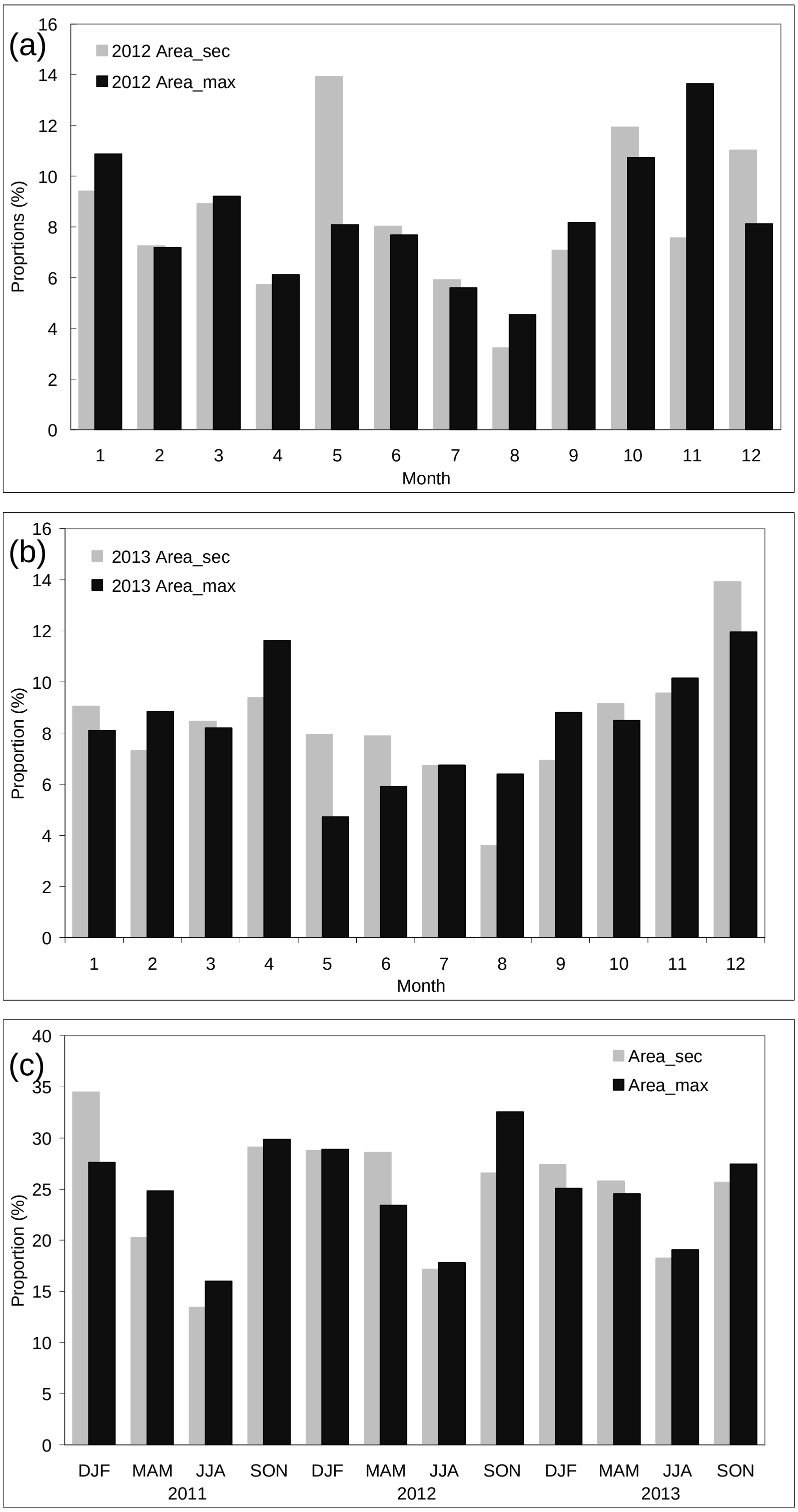

Figure 6. Proportions of flashes detected by WWLLN in Area_max and Area_sec: monthly (a) in 2012 and (b) 2013, and (c) seasonally in the period 2011-2013.

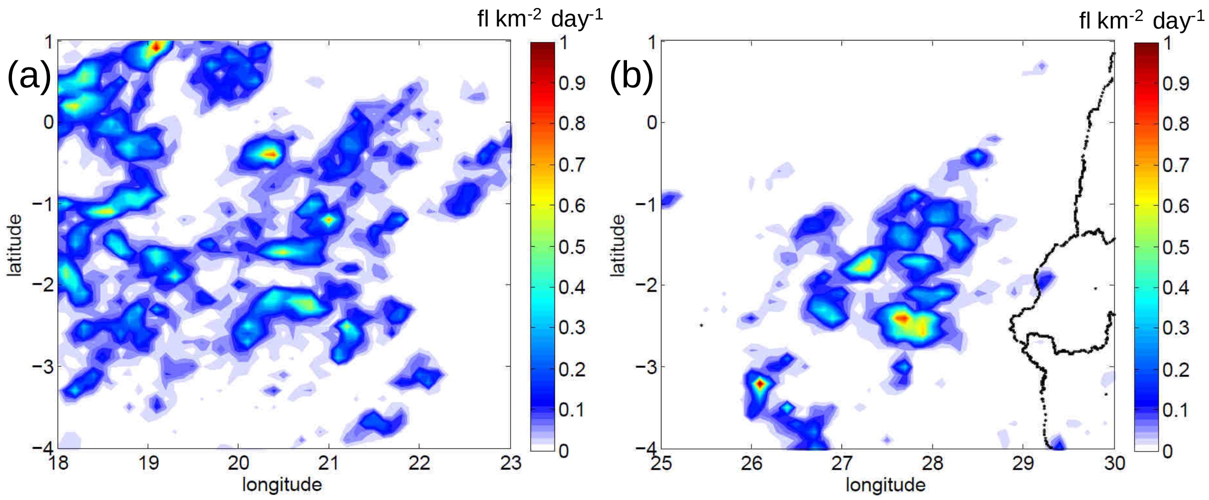

Figure 7. Density of lightning flashes (fl km^{-2} day^{-1}) detected by WWLLN on 25th of December 2013, (a) in Area_sec and (b) in Area_max.