Climatology of lightning activities across the Equatorial African region

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Abstract

In this study, it has been attempted to understand the role of various factors such as orography, moisture availability, aerosol nucleation, and atmospheric instability behind the spatio-temporal distribution of lightning properties over the Equatorial Central African region which experiences the most frequent lightning activity globally. Detailed statistical analysis using high-resolution satellite observations reveals very high lightning frequencies along the Virunga Mountain ranges during the summer season owing to its orographic advantage while the maximum flash radiances are observed over the relatively low-lying Congo River Basin during the month of June because of high moisture, instability, and aerosol availability in that region.

1. Introduction

Severe convective thunderstorms are a very common and prominent climatic feature over the tropical regions globally, and they are typically followed by several byproducts such as wind gusts and extreme rainfall [1-2] which again poses a lot of socio-economic hazards. But compared to the others, lightning appears to be the most damaging factor primarily due to the uncertainty in its position and timing during such extreme events. In last few decades many studies have been conducted globally to understand and predict such thunderstorm phenomena [3-6], but practically, the number of in-depth studies addressing lightning in a holistic manner is very rare.

Recently, a few studies have started utilizing satellite remote sensing tools for lightning research globally. While some of them investigated the spatial distribution and long-term trends of lightning, the others have tried to unravel a list of probable factors controlling it [7-9]. Some premier studies in this field have commented that mountainous regions normally experience orographic lifting which in turn may lead to intense rain and lightning [10]. Similarly, another school of thought has emphasized that specific types of in situ or transported aerosols can help in cloud formation leading to severe lightning [11].

In a few recent studies over Africa, it was revealed from low resolution lightning datasets that the eastern part of Congo Basin near the DR Congo and Rwanda border experiences the most frequent lightning flashes globally and further, the spatiotemporal distribution of lightning activity, in this region is controlled by a combination of several factors, such as the movement of ITCZ, and the orientation of the African Easterly jets [12]. Another study examined the diurnal variation of lightning and observed that most of the lightning flashes tend to occur during the afternoon hours between 13-16 LST. But in terms of long-term trends, the number of days with extreme lightning occurrences is increasing which has been attributed to the recent surge in greenhouse gas induced global surface warming [13]. However, a third study has reported a ~40% rise in thunderstorm frequencies due to recent climate change over Central Africa and this is also found to be strongly correlated with their corresponding moisture and instability trends [14].

However, the equatorial African sector remains a hot topic of research owing to the dearth of ample studies in this region. Besides, the available studies also fail to produce a holistic understanding about the underlying physical mechanisms controlling lightning as they could not pinpoint the exact location as well as the seasonality of lightning occurrences and intensity due to the extremely poor resolution of the gridded dataset used. Hence, the present study aims to understand the spatial-temporal distribution of the lightning occurrences on a daily, monthly, and annual scale using very high-resolution satellite passes. Next, the spatial distributions of various factors such as aerosols, instability, moisture availability, and orography has been studied to correlate lightning evolution with respect to each of these parameters at different timescales.

2. Dataset

For the present study, the lightning frequency and intensity datasets are utilized over the equatorial African region from ~95800 passes of Lightning Image Sensor (LIS) inside the Tropical Rain Measurement Mission (TRMM) satellite during the years 1998-2014. More information on this data is available from previous research [15]. This dataset has been averaged over 0.25X0.25-degree boxes here. The Lightning frequency is measured as flashes per square km while intensity is denoted in Joule per metre^2.

Secondly, this study utilizes the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, ERA5 [16] reanalysis datasets at 0.25 degrees resolution to depict the complex relationships between lightning and its underlying metrological factors. Finally, gridded datasets of aerosol properties like aerosol optical thickness (AOT), black carbon (BC), dust, organic carbon (OC), and sulfate are obtained from MERRA-2 modeled datasets provided by NASA. The reliability of these aerosol products can be authenticated from past studies [17].

3. Results and Discussion

3.1. Spatio-temporal variation of lightning

As mentioned in the previous section, high resolution lightning observations have been processed over equatorial African region (10ºN – 10ºS, 10ºE-30ºE) during the period January 1998-December 2014. Here it may be noted that currently, non-quality-controlled LIS datasets from the International Space Station are also available from the year 2017. Yet, these datasets were not considered along with the TRMM satellite-based LIS data owing to a huge difference in average lightning frequency magnitudes between the sources.

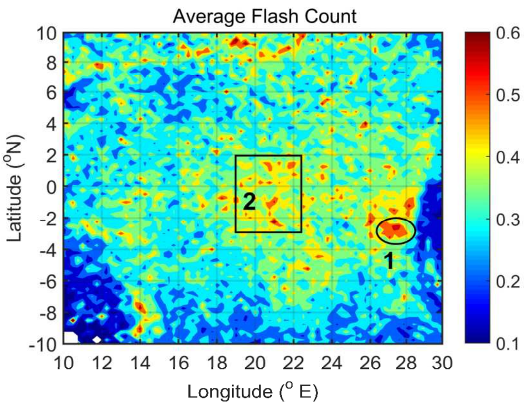

Figure 1. Average annual flash rate spatial distribution over the equatorial African region during 1998-2014.

So, at first, a spatial average map of lightning frequency is depicted to pinpoint all the hotspots of lightning within the study region as shown in Figure 1. Accordingly, two bright spots having too many lightning occurrences have been detected and henceforth have been referred to as region 1 and 2 (R1, R2) respectively. The first patch R1 represents a very bright but localized patch inside the area 1.5ºS - 3ºS and 27.5ºE – 29ºE. This region is nestled in the Virunga Mountains of DR Congo and according to climatic and previous research records, this place turns out to be the most lightning-prone region globally. On the other hand, the second one or R2 is a much larger region with slightly lesser lightning activity than R1 and it is situated between 3ºS – 2ºN and 19ºE – 21ºE. This sits directly above the Dense Congo rainforest, in Congo Basin, through which the Congo River flows.

At the next step, the seasonal variations of all the lightning properties namely: frequency, intensity, and peak radiances (represented by their 90th percentiles) are studied over the entire region (hereafter referred to as Whole) along with R1 and R2 and the results are depicted in Figure 2. This analysis reveals the existence of 2 maxima for flash rates, one in late February and the other but much smaller one in September. These maxima can be attributed to the existence of ITCZ over the entire region during early March and late September.

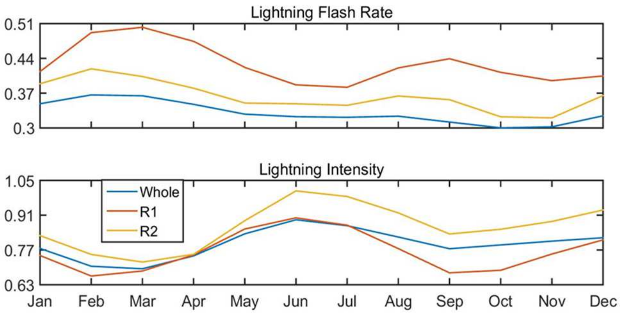

Figure 2. Monthly variation of lightning properties over various regions (a) Lightning frequency (b) Radiance.

But on the other hand, the average lightning intensity values are found to be the lowest during February and September months while its maximum is found during the relatively cool and dry month of June (when flash frequency values are minimum). This means that months of February experience ample lightning with minimal strength while relatively fewer but stronger ones are observed during June.

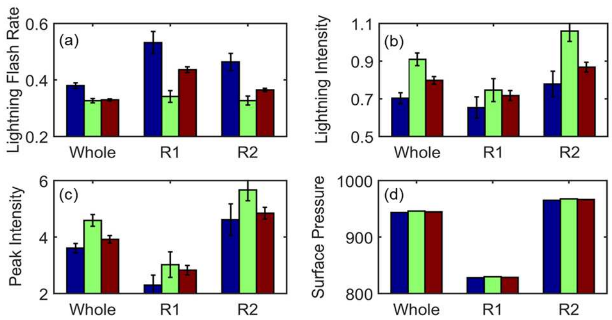

Figure 3. Seasonality of lightning properties and surface pressure over all study regions

This seasonality is also clearly depicted from the seasonal averages of lightning properties during February, June, and the entire year in Figure 3. It is observed that lightning flash rates are always the highest over February and the maximum lightning flash frequency in R1 is ~20% higher than R2. This spatial disparity may be attributed to the impact of orographic convection happening over mountainous slopes (as the surface pressure in R1 is 830 hPa compared to 950 hPa over R2 which implies a forced ascent of moist air by at least 1200 m compared to the rest of the central African region). Many previous research attempts have already argued that the presence of orographic lifting with minimal aerosol nucleation support discounts the necessity of strong convection to lift the prevailing moisture aloft to create clouds and lightning in various regions of the globe. But on the other hand, the average intensities of lightning radiances are found to be much higher during June and more importantly, the maximum average radiance values are ~30% higher over R2 compared to R1. Next, peak lightning radiance datasets are observed the results further accentuate this fact as the peak radiance values over R2 during June are extensively higher (~60%) than R1. Now this unprecedented spatial diversity in radiances hints towards the fact that the strength of lightning depends primarily on the number of charged hydrometeors in the mixed phase of cloud region; hence it is solely controlled by the moisture availability at that region. Similarly, as R2 is present in a relatively low-lying area with plenty of access to nearby water bodies such as the Congo River Basin and its proximity to the Atlantic; hence it is expected to experience much higher intensity compared to a dry and mountainous region (R1) both in seasonal and annual scale.

3.2. Physical mechanisms behind lightning occurrences over equatorial African region

In accordance with the above, it becomes highly important to investigate the subtle relationships between lightning and all its responsible factors; hence all those parameters have been plotted both seasonally and annually in Figure 4. The seasonality of the CAPE which primarily dictates the potential of the atmosphere to mature into thunderstorms depicts quite high values (above the classical threshold of 1500 J/kg for cyclogenesis) throughout the year in R2; but the highest values are observed during the summer season (February). However interestingly, these values are almost double of what is observed over R1. This is because, boundary layer moisture supply and surface temperature play the most crucial role behind the formation of Cumulonimbus clouds where lightning occurs. As R1 is present at ~1200 m above R2 hence its surface heating component is much weaker, next it's relative distance from water bodies further makes it more difficult for the atmospheric instability to mature; hence this observed disparity in lightning. Next the moisture content values are observed and as expected, R1 experiences much lower values while R2 depicts a very moist climate irrespective of season. This constantly high value of TCWV even in June can be considered as a primary reason why peak radiance in R2 manages to be ~60% higher than R1 even in the absence of an orographic advantage like R1. Another point to note is that R1 manages to get lightning radiance values much higher than the Himalayas or Andes mountains according to previous studies because of higher moisture availability and lower peak altitude compared to others.

Now, it is known that lightning activities predominantly occur due to interactions between ice and graupel particles; hence the total ice and liquid water content is next studied. TCIW (Total Column Ice Water) content is not much different between the regions, however the values are always higher during the local summertime in February. This is mainly because an ample amount of surface heating and instability is required to lift the moisture to above 6 km height which is clearly available during the summer season (recall their CAPE and TCWV values). Next, cloud liquid water content follows the pattern of TCWV and exhibits higher values over R2 than R1; but here interestingly, June values are much stronger than during February which will be explained in future sections. A similar pattern is also observed with respect to mid cloud cover (MCC); but there the average values over R1 are much higher than R2. This is because, MCC just considers the presence of cloud and in that case, the mountain slopes in R1 always experience orographic lifting, hence higher MCC. So, this may also be prime reason why lightning occurrences are higher over R1 though its intensity is much lower than R2. Finally, in case of the mixed layer Relative Humidity (RH), all the regions experience comparable RH of 60% during the summer season which may be attributed to moisture transport from the neighboring seas owing to strong sea breeze effect.

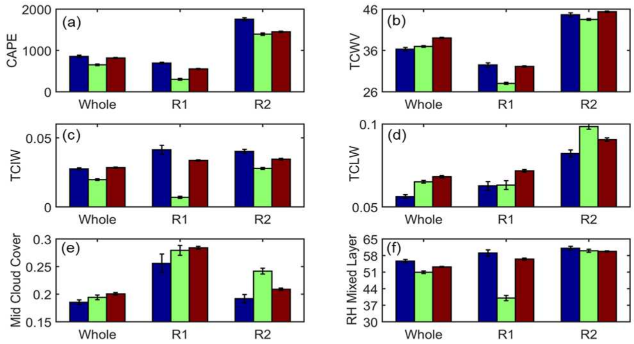

Figure 4. Seasonality of various meteorological factors which modulate lightning over all study regions. (a) CAPE, (b) TCWV, (c) TCIW, (d) TCLW, (e) Mid Cloud Cover and (f) Relative Humidity inside the mixed layer

But interestingly, the mixed layer region in R1 becomes drastically drier during the local winter in June while nothing happens in R2. This may be because of the dearth of rivers or water bodies supplying moisture to R1 in absence of strong breeze effect while R2 continues to receive sufficient moisture even then from the Congo River. This hypothesis if proved true in subsequent research can also explain how peak radiance values over R1 during June are only about half of R2.

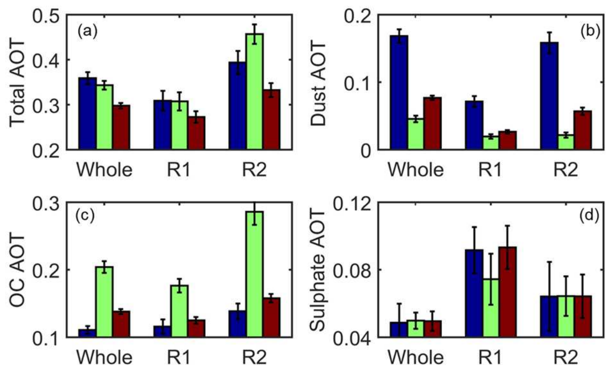

Figure 5. Seasonality of the aerosol components effecting lightning over all study regions. (a) Total AOT, (b) Dust AOT, (c) OC AOT and (d) Sulphate AOT

Finally, the secondary impact of aerosols is discussed in Figure 5 where it is observed that R2 experiences Total Aerosol Extinction (AOT) values which are ~50% higher than R1 particularly during the month of June. This is quite expected from the observed lightning spatial disparities because aerosol particles of Sulphate, Dust, or Organic Carbon type have already been indicated in previous research attempts to act as good ICN or CCN which assist in ice and graupel particle formation and hence lightning. Further, the presence of more nucleating aerosols during June also partly explains how wintertime conditions experience stronger lightning radiances despite weaker instability and moisture content. Next, the aerosol components are observed separately which reveal that during summer, the dust component is stronger than the other species and as dust aerosols act as good ICNs hence it manages to create more lightning occurrence. However, the amount of charges produced during any lightning flash mainly depends on the graupel or liquid concentration which again is controlled by the availability of CCN forming aerosols such as OC or Sulphate. Now since, the month of June experiences much higher amounts of both these aerosols, hence it becomes easier to explain why lightning radiances are stronger at that time. However, this aspect still needs to be studied to understand why OC or Sulphates are more prominent during June while dust is more prevalent in February over the present study region.

4. Conclusions

The present study seeks to explain the spatio-temporal distribution of lightning frequency and intensity over the Equatorial Central African region which experiences the most frequent lightning activity globally using very high-resolution datasets obtained from TRMM satellite during 1998-2014. The results indicate very high lightning frequencies along the Virunga Mountain range during summer while the maximum flash radiances are observed over the Congo River Basin during the month of June. The stronger radiance observed over the Congo Basin has been attributed to high moisture, instability, and aerosol prevalence particularly during the dry and cool season of June. But on the other hand, regions lying along the Virunga Mountain ranges experience extremely frequent lightning occurrences because of its orographic advantage despite the dearth of other components. A future study in this regard will further aim to study the other aspects of lightning over the equatorial African region such as its climate variabilities and its relationship with other associated factors like anthropogenic global warming, monsoon strength, and teleconnection influences.

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