

LIGHTNING ACTIVITY OVER LEGON AND ITS APPLICATION TO RAINFALL ESTIMATION

BY

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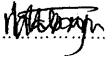
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**THIS THESIS/DISSERTATION IS SUBMITTED TO THE
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DEGREE**

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DECLARATION

This thesis is the result of research work undertaken by William Martey in the Department of Physics, University of Ghana, under the supervision of Prof. K. Oduro Afriyie and Dr. V. C. K. Kakane.

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DEDICATION

To my parents, who have raised me to be a knowledge-seeker.

And to my family and friends, who have always encouraged me to continue learning and sharing knowledge.



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ABSTRACT

Lightning is an important component in the global electric circuit of the earth. It is a leading cause of outages in electric power and telecommunication systems, of forest fires and of delays in aircraft missions.

A lightning sensor operating at a radio frequency of 300 kHz was constructed and used to study the occurrence of lightning in and around the University of Ghana campus during thunderstorms. Rainfall figures during each thunderstorm were also recorded.

Data was collected over a period of two and half months (from May 13 to August 2, 2008). It was observed that the number of strikes correlated with the amount of rainfall, a larger number of lightning strikes being associated with a greater amount of rainfall. Polynomials of various degrees were fit to the data and the cubic polynomial ($y = 2E-05x^3 - 0.0037x^2 + 0.4287x - 2.3078$) was found to yield the best compromise between correlation coefficient and coverage of the amount of rainfall (y) and the number of lightning strikes (x) during the study period. The experiment can be used to estimate the amount of rainfall (y) if the number of lightning strikes (x) during a thunderstorm is known assuming that there was rainfall during the period.

A similar analysis performed on lightning flash rate and rainfall amount did not indicate a strong correlation.

The maximum number of lightning strikes recorded during the study period was 200 ± 1 and this occurred on the night of May 18, 2008 when most parts of Accra were flooded. Coincidentally, a maximum of 117.3 ± 0.1 mm rain was recorded on the same day at

Legon. The minimum number of lightning strikes for the study period was 15 ± 1 occurred on June 13, 2008. On that day, the amount of rainfall was 15.2 ± 0.1 mm.

CHAPTER ONE

1.0 INTRODUCTION

Lightning is probably one of the most widely studied natural phenomena, first for its power of destruction and then for its magnificent appearance. Initially the lightning phenomenon was considered as a messenger or a symbol from divinities in different cultures (religion and/or mythologies); in modern times this belief has been replaced by scientific knowledge, and researchers in many countries around the world have contributed to human understanding of the lightning discharge. Nevertheless, the phenomenon of lightning is still not completely understood and some of its processes are yet to be fully explained. For example, the origin of the accumulation of charge in the clouds, the effects of the strike point on the associated electromagnetic fields, as well as the consequences of these parameters on natural and human made systems are still the subject of scientific debate and controversy.

Each year, lightning is responsible for the deaths of approximately one hundred persons, injuries to several hundreds more, and millions of dollars in property damage in the United States [Goodman *et. al.*, 1992]. In Ghana, damage caused by lightning is often overlooked and only a few cases are officially reported. Lightning killed six Ghanaian sailors off the coastal shores as reported by the Daily Graphic on the 2nd of June 2007 [Daily Graphic, 6/02/2007]. Another three were struck by lightning at Cantonments a suburb of Accra during a heavy down pour on the 20th of September, 2007 [GNA, 21/09/2007].

On the lightning chart obtained from the combined observations of the NASA OTD and TRMM-LIS earth orbiting satellite sensors during the period of April 1995-February 2003 (Figure 1.1), Ghana is considered a lightning prone country with an average value of 20-40 lightning flashes/km²/yr. It is therefore important that the occurrence of lightning in Ghana be studied closely.

High Resolution Full Climatology Annual Flash Rate measured in
flashes/km²/yr

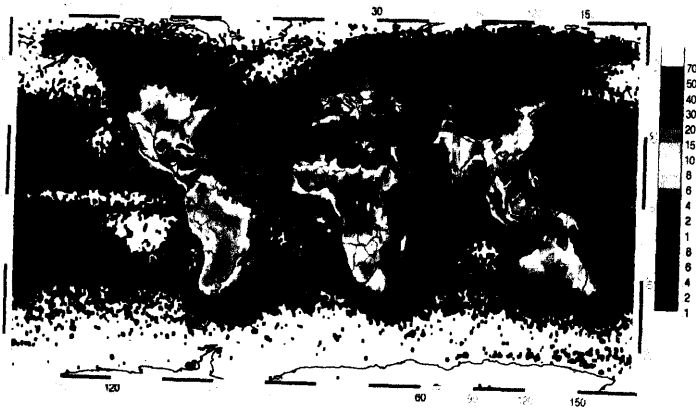


Figure 1.1: Global distribution of lightning from the combined observations of the NASA OTD and TRMM-LIS earth orbiting satellite sensors (adapted from Wikipedia, 2007).

1.1 LIGHTNING: Description of the lightning phenomenon

Lightning is known to contribute to the electric equilibrium between the earth and the atmosphere. It is also believed to be at the origin of life itself, as stated by Uman:

“Lightning has likely been present for the period of time during which life has evolved on earth, and, in fact, lightning has been suggested as a source for generating the necessary molecules from which life could evolve” [Uman, 1987]. A lightning discharge is a fantastic visual spectacle, but it is, at the same time, the cause of forest fires, of human and animal casualties, of damage to electric and telecommunication systems, etc. A thunderstorm (thundercloud or cumulonimbus) is defined in the literature as a cloud with a particular concentration of charges.

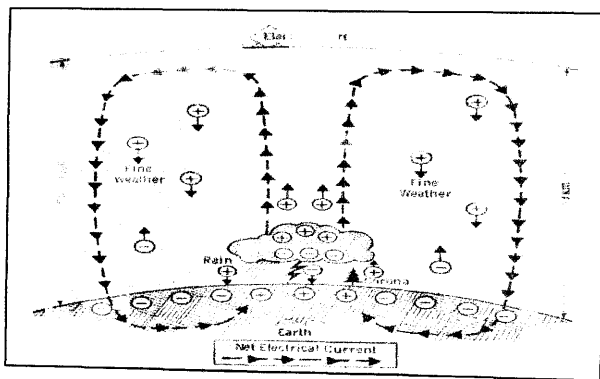


Figure 1.2: Electrical equilibrium between the earth and the atmosphere through lightning (adapted from Uman, 1987).

1.2 Clouds and Cloud Types

Clouds are condensations of water vapor into water droplets or ice crystals in the atmosphere. Cloud shapes and the dynamics of their formation are accurate indicators of important atmospheric properties, including air stability, moisture content, and motion.

Clouds are divided into families of high level, middle level, low level, and vertically developing clouds, and are classified again, using their general shape.

High level clouds include cirrus, cirrostratus, and cirrocumulus clouds that occur at altitudes between 6,000 and 12,000 meters above the terrain [Perrie, 1950]. Middle level clouds include altostratus, altocumulus, and nimbostratus clouds that occur between 1,800 and 6,000 meters [Perrie, 1950]. Low-level clouds include stratus and stratocumulus clouds that occur between the surface and 1,800 meters [Perrie, 1950]. Vertical development clouds include cumulus and cumulonimbus clouds, and range in their development from the surface to 14,000 meters. The heights of the bases of the clouds used to designate cloud families can vary with latitude. At extreme northern or southern latitudes, high altitude family clouds can be observed at much lower altitudes.

In general, cloud shape is determined by the method of cooling to reach condensation and the forces of winds that can shear or tear the cloud. Cloud opacity (i.e., whether it is light or dark) is a function of cloud thickness [Mason, 1971].

Cirrus clouds occur at high levels and are generally wispy and elongate in form. Vertically rising air is unstable and gives rise to cumulus cloud formation. Cumulus clouds are billowy. Stratus clouds (i.e., stratified clouds) are heavily layered and often

appear in sheet-like formations. With regard to cloud nomenclature, nimbus clouds (e.g., clouds with the prefix nimbo or the suffix nimbus) are thunder storm and rain-producing clouds.

High clouds, namely cirrus, cirrostratus, and cirrocumulus, are composed of ice crystals and dust or pollution particles. The particles often serve as centers of crystallization or condensation nuclei. Cirrus clouds often produce "mares' tails" that are tail-like wisps of ice crystals. Cirrostratus clouds, because they are thin and the ice crystals act to both reflect and refract sunlight, are often associated with halos of ice crystals that appear to encircle the Sun or Moon. Cirrocumulus clouds often appear as patch-like thin clouds.

Middle level clouds including altostratus, altocumulus, and nimbostratus, are composed of water with some ice crystal formation near cloud tops. Both middle level and low level clouds may be composed of super-cooled water (water below freezing) that has not yet crystallized around a condensation nucleus. Altostratus clouds often present a bluish-layered appearance. Depending on thickness, altocumulus clouds often have white or gray layers that appear in washboard or wave-like formations. Atmospheric instability and convective air currents can result in the formation of altocumulus castellanus clouds, a form of altocumulus that often appears as isolated cumulous clouds with billowing tops. Another form of altocumulus cloud, a standing lenticular altocumulus cloud, is formed by turbulent updrafts of air uplifted by terrain barriers (e.g., mountains, ridges, etc.). Although dynamic, the standing lenticular altocumulus cloud formations appear static or "standing" over the terrain feature leading to their formation. Nimbostratus clouds often appear as heavy, gray, moisture laden cloud layers

Low-level stratus clouds are usually gray clouds associated with precipitation and fog. Stratocumulus clouds present the familiar, cotton ball-like cumulus shapes in an elongate form (a cumulus shape drawn out by shearing winds).

Clouds with extensive vertical development, namely cumulus and cumulonimbus clouds, often present a gradient of ice and water. Rapid updrafts and downdrafts (ascending and descending of air) allow ice crystals to appear at much lower levels than would be expected by atmospheric temperature. Although arising from convective currents, cumulus clouds often form in fair weather and do not show extensive vertical development. Cumulus clouds present flat bases and curved or domed tops. More extensive vertical development occurs as atmospheric instability increases. Highly developed cumulus clouds often present mushroomed or cauliflower-like tops, and can ultimately produce rain. Cumulonimbus clouds form under unstable atmospheric conditions. Cumulonimbus clouds are dark clouds with anvil like tops sheared by very high altitude winds. Heavy turbulence, violent rains, lightning, and thunder often accompany cumulonimbus clouds. Particularly unstable and violent clouds can occur in cells capable of spawning tornadoes.

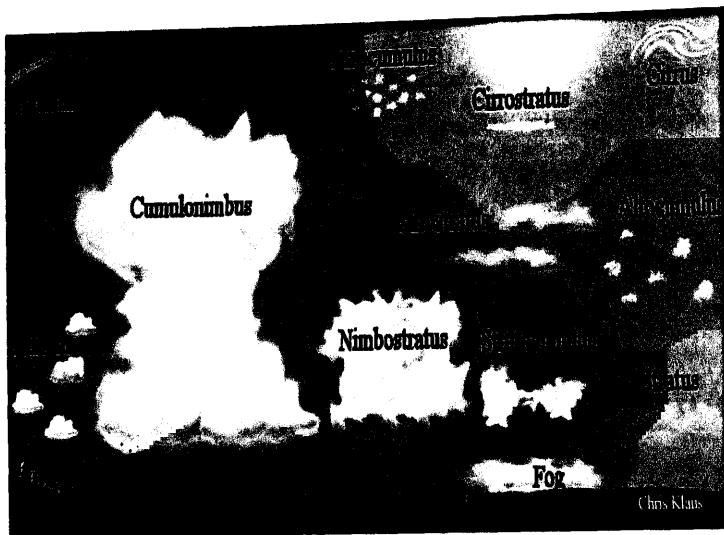


Figure 1.3: Types of clouds. Picture adapted from Chalquist (2007)

1.3 Cloud electrification and Charge Structure

Currently, there are a variety of hypothesized mechanics that produce cloud electrification, but the most accepted one involves ice and super-cooled liquid water. The graupel-ice mechanism appears most capable of producing the magnitude of electric fields found in thunderstorms [MacGorman and Rust, 1998, 2002]. In this mechanism, graupel pellets grow by riming in a super cooled liquid water environment, and collide with ice particles to produce charge transfer. Then, the differential fall speeds of the

larger graupel versus the smaller ice crystals produce charge separation where the graupel would fall to the lower portion of the cloud and the ice particles remain suspended aloft.

Several laboratory experiments have investigated the conditions by which particles obtain charge during collisions using the non-inductive charge transfer mechanism [Takahashi, 1978; Saunders *et al.* 1991; Saunders, 1994]. The Takahashi lab experiments indicate that at temperatures warmer than -10°C , the rimed particle (usually graupel) will charge positively for a large range of liquid water contents. However, below -10°C , the sign of the charging depends on liquid water content. At high liquid water contents, and very low liquid water contents, the rimed particle will charge positively. Otherwise, it is expected to charge negatively.

In most thunderstorms, the typical electrical structure produced by charging is either an ordinary dipole or tripole [Williams *et al.*, 1989]. This consists of a dominant lower main negative charge region with a positive charge region above. In the tripole, there is also a smaller, more localized, lower positive charge region below the main negative region, perhaps due to reverse charging on the graupel at low temperatures. However, more recent studies using balloon electric field measurements report that outside of the updraft, the electrical structures are more complex, and may contain up to six layers of charge [Stolzenburg, 1990]. There is also a negative screening layer found at the top of many thunderclouds.

Three parts in the cloud can be distinguished: first, a main negative charge region located at the lower part of the cloud; second, a main positive charge region displaced to the top of the cloud and, finally, a small center of positive charge remains in the lower part of the

cloud. It is believed that this third charge concentration has the function of initiator of the lightning discharge. In Figure 1.4, the charge distribution inside a thundercloud is shown.

At ground level, the accumulation of charges in the thundercloud produces a concentration of the electrostatic field below the cloud (lower waveform in Figure 2.3).

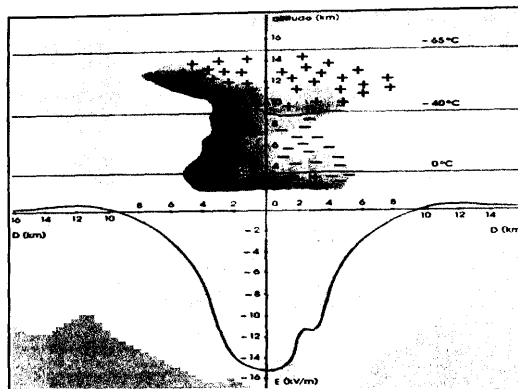


Figure 1.4: Charge separation within a thunderstorm cloud (adapted from Gary, 1995).

The electrostatic field associated with a thundercloud and the displacements of these clouds by the action of the air have helped researchers define methods of prediction of lightning discharges. Today, one can find systems which are capable of measuring the electrostatic field in the environment, and differentiate a thundercloud from other cloud types. One can use the static electric field at ground level to infer when enough charge has accumulated in the thundercloud to start a lightning process. These systems then alarms to alert outdoor workers of the imminent danger of lightning, thus preventing accidents or damage to equipment. High variability in the lightning parameters makes

this phenomenon inherently difficult to predict and these so-called early warning systems are therefore not one hundred percent reliable.

When the electric field level necessary to start the process of a lightning discharge is attained, several scenarios are possible: First, lightning discharge can be produced and stay confined inside the same cloud; secondly the discharge can take place between separate clouds; thirdly, the discharge may occur between the cloud and the air; or finally, the discharge may be produced between the cloud and the ground.

Even though cloud-to-ground lightning discharges are not the most frequent discharges produced during a thunderstorm, they are the most studied as they are responsible for direct and indirect damages to systems at ground level, and they are more easily observed and photographed. We will focus our attention on that type of lightning discharge, which is produced between thunderclouds (cumulonimbus) and ground.

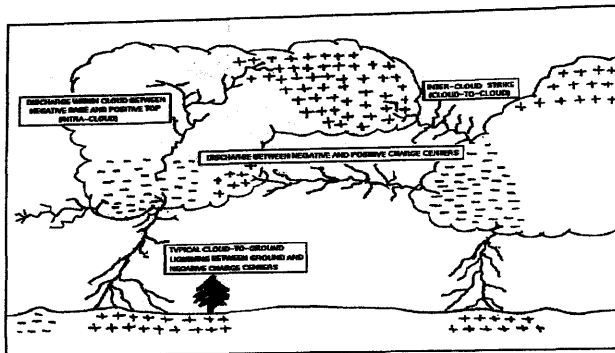


Figure 1.5: Diagram showing the types of lightning discharges (adapted from Christian *et. al.*, 1989).

The figure above (figure 1.5) is a pictorial representation of the various types of lightning discharges.

Berger cataloged cloud-to-ground natural lightning in four categories as a function of the direction of the motion of the initial leader (upward or downward), and the sign of charge deposited along the channel by that same initial leader (positive or negative) [Berger, 1975]. This classification is illustrated in Figure 1.5. The first category, cloud-to-ground lightning moving negative charge to the ground, is the most common (90% of the world-wide cloud-to-ground lightning). The second and third categories are initiated by leaders that move upward from the earth (ground-to-cloud lightning). Ground-to-cloud (upward) flashes are relatively rare and generally occur either from mountain tops and tall man-made structures, or they can be triggered from rockets launched toward thunderstorms [Uman, 1987]. Upward flashes may be identified by the upward branching of the flash if a photograph of the flash was taken or by the continuing currents of milliseconds that

may be followed immediately or after short current interruptions by one or several impulse currents (return strokes). Downward flashes, on the other hand, branch downward and do not produce pre-discharge currents lasting more than a few milliseconds [Berger et al., 1975]

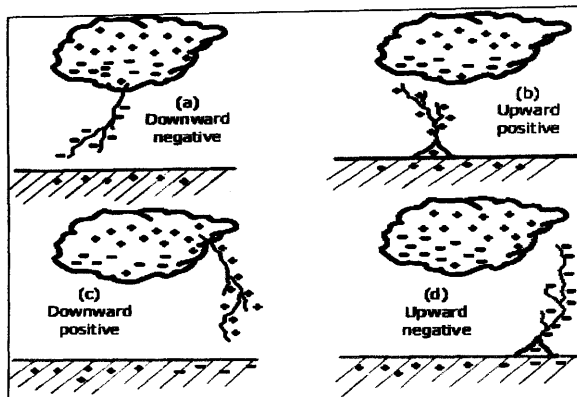


Figure 1.6: Lightning stroke classification according to Berger [Berger et al., 1975].

A complete lightning discharge is known as a flash and its time duration is about half a second. A flash is composed usually of several return strokes. Each stroke lasts a few hundred microseconds and, in multiple-stroke flashes, the separation time between strokes ranges from a few milliseconds to a few hundred milliseconds with a mean value on the order of 40 milliseconds. When the separation time between strokes is close to 100 milliseconds, lightning appears to "flicker" in the sky, because the human eye can resolve the individual strokes [ELAT, 2002].

The return stroke process is initiated when the first preliminary discharge at the lower part of the thundercloud appears, then, a series of processes, represented in Figure 1.7 for a negative cloud-to-ground lightning discharge, can be distinguished [Uman, 1987].

The preliminary discharge starts the process and it is followed by the stepped leader. The stepped leader propagates down in a series of discrete steps. The stepped leader branches in several directions during its progression to ground producing the downward-branched geometrical structure. When the leader approaches the ground, the electric field at pointed objects on the ground exceeds the breakdown value of the air and one or more upward-moving discharges are initiated (upper-discharges on figure 1.7). Finally, one of these upper-discharges contacts the leader (usually some tens of meters above ground). This is called the attachment process. The leader is connected to the ground potential, and it starts to be discharged by a ground potential wave propagating up through the leader path, a process known as the first return stroke. After about 100 μs , the ground potential wavefront has discharged the leader and the first return stroke is over. If additional charges are still available in the cloud, one or more leader-return stroke sequences may ensue, this time following the same ionized path previously created by the first return stroke. The subsequent leaders are called dart leaders. Dart leaders and subsequent return strokes are usually not branched.

Often, a current of the order of 100 A continues to flow for a few to tens of milliseconds after a return stroke. This current flow is called the continuing current which produces a slow, more or less linear, field change in close electric field records and which is responsible for forest fires.

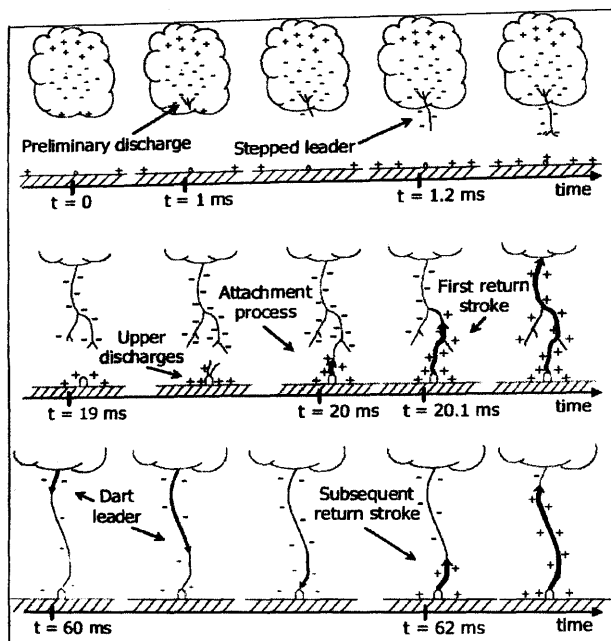


Figure 1.7: Return stroke process for a downward negative cloud-to-ground lightning (adapted from Uman, 1987).

A schematic representation in time of a cloud-to-ground lightning discharge with a first and two subsequent return strokes is presented in Figure 1.8a, and Figure 1.8b shows a streak-camera photograph of a 12-return stroke flash.

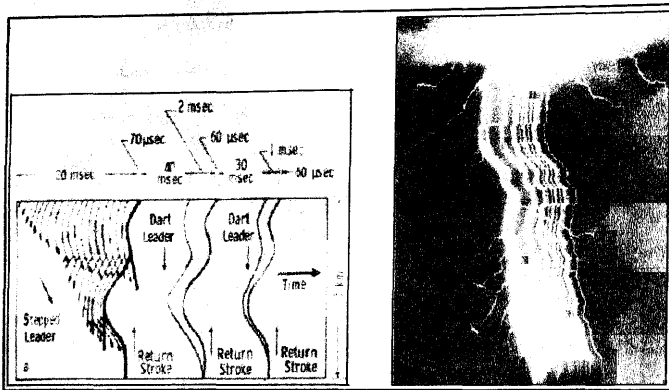


Figure 1.8: (a) Drawing of the luminous features of a lightning flash below a 3 km cloud base as would be recorded by a streak camera. (b) Streak camera photograph of a 12-stroke lightning flash (Adapted from Uman, 1987).

1.4 Lightning return stroke parameters useful for electromagnetic modeling: Measurement techniques



The progress made in the instrumentation and the work of researchers permitted the evolution of knowledge on lightning discharges in several directions. Photography was probably one of the first experimental methods employed to observe the nature of lightning flashes. The invention of the double-lens streak camera in 1926 by Sir Charles Vernon Boys in England allowed the observation of the direction and the speed of lightning discharges.

Basalt is largely employed to measure lightning currents in electric lines struck by lightning because of its low cost [Gary, 1995; Uman, 1987]. For modern lightning studies, sophisticated instrumentation is employed able to measure lightning discharge parameters such as electromagnetic fields at different distances, speed of the return stroke at different heights, return stroke current at the base of the channel, branches of the channel, lightning luminosity, optical spectrum of the lightning channel, temperature and water vapor content of the lightning channel (spectroscopic system), etc. This section will focus only on the first three parameters (electromagnetic fields, speed of the return stroke and return stroke current), which are directly involved in the modeling of electromagnetic effects associated with lightning return strokes. We will briefly describe experimental techniques used today to measure these parameters.

1.5 Electromagnetic field

The electromagnetic fields associated with a lightning return stroke are characterized by a particular waveform signature which depends principally upon the distance to the impact point of the lightning return stroke, which makes them easily identifiable. Lightning discharges have typical time durations of the order of one second, while the individual physical processes comprising these discharges and described in the previous section can vary on a millisecond, microsecond, or even sub microsecond time scale. It follows that variation of current and charge associated with a lightning flash produce “wideband” electric and magnetic fields with significant frequency content in a frequency range from 0.1 Hz to well over 10 MHz [Uman, 1987].

1.6 Electrical field-changes during a lightning flash

If the distance L to an observing station is large compared with the dimensions and height of the thunder-cloud, and if ionospheric effects may be neglected, the vertical electric field at the Earth's surface at any instant t is given by

$$F(t) = \frac{M}{L^3} + \frac{1}{cL^2} \frac{dM}{dt} + \frac{1}{c^2L} \frac{d^2M}{dt^2}$$

where all the electrical quantities are measured in e.s.u. and L in cm, M is the electric moment of the cloud, and c is the velocity of light in cms^{-1} .

The first term represents the electrostatic component and is proportional to the electric moment, M of the discharge and varies inversely as L^3 ; the second term is the electromagnetic induction term and depends on current in the discharge and varies inversely as L^2 ; and the third term is the electromagnetic radiation term which depends on the acceleration of the charges involved, and varies inversely as L . Thus, for close discharge, the electrostatic field predominates, while at large distances the radiative field is predominant [Mason, 1971].



1.7 Lightning Sensors

Lightning sensors detect and locate electrical activity in thunderstorms using a number of different methodologies. These include direction finding (DF) [Krider et al., 1976], time-of-arrival (TOA) techniques [Lee, 1989], a combination of these two [Cummings et al., 1998], and interferometry methods [Hayenga and Warwick, 1981]. All techniques need a number of sensors within a network to get reliable data on the location of a lightning flash. The DF method uses two orthogonal magnetic loop antennas, where the azimuth angle to the flash is obtained by simple trigonometry. The TOA method uses the small differences in the arrival times of the radio wave at different stations to determine the optimum distance to the flash from a network of synchronized stations. Today with GPS timing, the TOA method supplies more accurate locations compared with the DF methods. However, today, combinations of both methods are often used to enhance the accuracy of lightning detection networks.

1.7.1 Very High Frequency (VHF) sensors

By using VHF sensors, the high-frequency components of the lightning discharge can be reconstructed in either two or three dimensions. While this method supplies great detail about lightning in individual thunderstorms, it cannot be used over large regional areas, and cannot supply other important information about the discharge peak current, charge, and polarity. Nevertheless, these systems offer great possibilities for early warning systems in regions with higher risk of losses (e.g. airports, industry, sport events, etc.)

[Kawasaki *et al.*, 1994]. These VHF systems provide information on the storm development, the intensity of the storm, and the likelihood of severe weather.

VHF direction finding is termed interferometry (IF) since the phase difference of signals arriving at different antennas is used in determining both the azimuth and elevation of the radiation emitted from the lightning channel [Shao *et al.*, 1995]. As with DF methods, the IF method of detecting the pulse location is less accurate than the TOA method.

The TOA method in the VHF band was first proposed by Proctor (1971), using at least 4 sensors spaced tens of kilometers apart, all with accurate timing. A more modern system using this methodology [Rison *et al.*, 1999] with GPS timing detects radiation around 63 MHz, during a 100 μ s time interval. If the radiation exceeds a noise threshold, the peak signal times are recorded with 50 ns time resolution using a 20 MHz digitizer accurately phase locked to the 1 pulse per second output of a GPS receiver. Events detected by at least 6 sensors are then located in three dimensional space and time.

VHF networks normally consist of 10-20 stations separated by tens of kilometers, all within approximately 60 km of the center of the network. Each station is elevated some 15 meters above the ground and detects radio frequency bursts in the frequency range from 60-150 MHz. Many different VHF systems have been developed, including the SAFIR, LDAR, LMA and PROFEO networks.

1.7.2 Very Low Frequency (VLF) sensors

Due to the lower attenuation of atmospheric radio waves at VLF frequencies (3-30 kHz) [Pierce, 1977], VLF sensors can be separated by hundreds to thousands of kilometers, while still being able to detect the VLF radiation emitted by individual lightning flashes. Many such regional networks using VLF sensors have been set up around the globe [Krider *et al.*, 1976]. The radio waves detected in the VLF range are known as atmospherics, or "sferics". Both DF and TOA methods can be used in locating the source of the VLF sferics, while the peak VLF field can be related to the peak current of the parent lightning.

The VLF sensors are either orthogonal magnetic loop antennas, or a vertical electric field whip antenna. The size can range from a few centimeters to tens of meters, depending on the sensitivity required. Using additional electric field sensors, the polarity (positive or negative) of the parent lightning can also be determined. Hence, VLF networks provide wide geographical coverage together with additional important information about the type and strength of the lightning flashes. These parameters may also have important uses in understanding which storms will develop into severe weather events.

Most lightning networks used today around the globe are of the VLF type, since they supply great regional coverage, reasonable spatial accuracy, while also providing additional information about the lightning return stroke (peak current, polarity, multiplicity, etc.).

The one disadvantage of using VLF sensors over large regions is that the sensors are sensitive primarily to vertically oriented lightning discharges, while the detection

efficiency of these flashes depends on the spacing of the sensors. Hence, much of the horizontal intra-cloud (IC) lightning is not detected by these large scale networks. Since intra-cloud lightning makes up ~70% of all lightning, VLF networks are limited in their ability to track the entire development of thunderstorms.

Nevertheless, they allow us to monitor thunderstorm activity at great distances from the sensors, and recent VLF networks have started to cover the entire globe [Rodger *et al.*, 2006]. An example of a network which uses VLF sensors is the WWLLN network (World Wide Lightning Location Network) which detects lightning activities over the entire globe. The WWLLN uses an improved time-of-group-arrival (TOGA) methodology for determining the time of arrival of the sferic at each station located hundreds of kilometers apart. Due to dispersion of the waveforms in the Earth-ionosphere waveguide, the normal TOA method leads to inaccuracies in the time the pulse arrives at the station, and hence the distance to the parent lightning. Using the group velocity allows for more accurate timing and for location errors of less than 10 km anywhere on the globe [Lay *et al.*, 2004, 2006].



1.7.3 Extremely Low Frequency (ELF) sensors

In the ELF (3-300 Hz) range the radio waves from lightning undergo very little attenuation, and hence manage to propagate around the globe a number of times before decaying into the background noise [Price *et al.*, 2007]. An interesting phenomenon, called the Schumann resonances (SR), occurs due to the constructive interference of these ELF as they propagate around the globe. Due to the circumference of the Earth (~40,000

km) the Schumann resonances occur at 8, 14, 20Hz, supplying a continuous measure of global lightning activity.

ELF sensors are normally a combination of horizontal magnetic induction coils, and vertical electric field sensors. The induction coils are approximately 1.5 meters long, and buried in the ground to reduce noise levels. The coils need to be sensitive at the pT (10^{-12} Tesla) level in order to detect global lightning signals. The vertical electric antenna is normally a ball-antenna 2-10 meters above the ground. Most ELF stations detect only the horizontal magnetic ELF fields, while a complete ELF station will observe three components of the electromagnetic field (H_x , H_y and E_z). Intense lightning discharges, associated with a large charge transfer and often high peak current [Ogawa *et al.*, 1966] often exceed the SR background level by a factor of 10. When these very intense lightning discharges can be isolated from the background global activity, it is possible to determine the source locations even when using only a single ELF station [Kemp and Jones, 1971].

The ELF lightning location can be obtained with either multi-station or single-station techniques. The multi-station techniques are more accurate, but require more complicated and expensive facilities, involving a network of direction finders or time-of-arrival sensors [Rafalsky *et al.*, 1995], as is the case with the VHF and VLF methods. Single-station ELF systems usually combine a direction finder with a source-receiver distance estimation technique, using the relationship between the electric and the magnetic field components [Huang *et al.*, 1999]. However, the location of the source lightning using ELF techniques has an accuracy of 500-1000 km when using a single-station

measurement. Although this is a fairly poor resolution, a single station can nevertheless supply real time global coverage of intense lightning flashes.

1.8 Objectives of this work

- Designing a high availability lightning sensor to detect and measure lightning intensity within the study area.
- Measuring the corresponding amount of rainfall during a thunderstorm over the study area.
- To do a regression analysis of the lightning and rainfall data to ascertain a possible relationship between them.

1.9 The study Area

The university of Ghana campus is located about 20 km from the coastal shores of Accra and about 25 km from the city centre. It is a typically tropical area with wet season spanning from the month of April through to July.

The campus has an average relative humidity of about 56% around 15:00 hr local time around 82% during 18:00 hr local time [Martey, 2005]. An average annual rainfall figure of about 200 mm is recorded in and around the campus [GMA, 2007].

CHAPTER TWO

2.0 LITERATURE REVIEW

Benjamin Franklin was one of the pioneers who conducted research into lightning and is owed to him the concept and the proof that lightning is an electrical phenomenon [Golde, 1977]. He endeavored to test the theory that sparks shared some similarity with lightning using a kite. Prior to his experiment, Thomas-François Dalibard and De Lours conducted a similar one at Marly-la-Ville in France as stated in Franklin's autobiography (written 1771-1788, first published 1790) [Franklin, 1964].



Kalb conducted research into cloud-to-ground (CG) lightning polarity and environmental conditions over the central United States [Kalb, 2007]. This study used radar data, and CG lightning data, to identify positive and negative storms that occurred in the region between the Rocky Mountains and the Mississippi River.

Out of all the variables used, cloud base height, dew point, 850-500 mb lapse rate, and warm cloud depth showed the most difference between the positive and negative storms. Positive storms tended to occur with lower cloud base heights, higher dew points, smaller 850-500 mb lapse rates, and lower warm cloud depths. Little trend was seen for CAPE, CIN, freezing level, lifted index, mean relative humidity, mid level relative humidity, precipitable water 0-3 km wind shear, 0-6 km wind shear, storm relative helicity, and potential temperature.

The strength of the differences seen between the positive and negative storms varied with the choice of percent positive used. Differences between the positive and negative storms tended to decrease when 10% was chosen (as compared to 30%), but they increased when 50% was chosen.

Peter studied the Quantitative measurement of lightning-induced electron precipitation using VLF remote sensing [Peter, 2007]. His work examined the detection of lightning-induced energetic electron precipitation via sub ionospheric Very Low Frequency (VLF) remote sensing.

Measurements of the VLF signal perturbations taken indicated that 90% of the precipitation occurs over a region $8^{\circ}\pm 1^{\circ}$ and $9^{\circ}\pm 1^{\circ}$ in latitudinal extent for the two time periods. The measured peak of the precipitation was poleward displaced ($6^{\circ}45'\pm 30'$ and $7^{\circ}45'\pm 30'$ for the two case studies) from the causative discharge. The onset delay and the duration of precipitation steadily increased with increasing L-shell, while the signal recovery time was independent of L-shell for the LEP events associated with both storms. The causative lightning discharges associated with the two storms were located at different latitudes.

Cannons and Kinsner [Cannons and Kinsner, 2004] wrote a paper entitled “Modeling of lightning discharge patterns as observed from space”. The paper examined the current progress in the development of lightning models, both at the microphysical and abstracted numerical levels. Their analysis suggested that lightning discharge patterns are multifractal in both space and time, and that percolation theory may be easily employed

to create lightning models for better understanding and prediction of the thunderstorm process.

Cumme studied lightning and ionospheric remote sensing using VLF/ELF radio atmospherics [Cumme, 1997].

The aim of this work was to develop and implement the necessary techniques to use spheric observations to determine the characteristics of the ionosphere and lightning. The vertical charge-moment change in sprite-producing discharges was measured quantitatively.

Pessi *et. al.* made investigations into the relationship between lightning and convective rainfall over the central Pacific Ocean [Pessi *et. al.*, 2007]. By using rainfall data obtained from TRMM's and Aqua's microwave sensors for a variety of storm systems and lightning data obtained from Pacnet, the preliminary results indicated that the ratio of lightning to rainfall rate shows a stable pattern over the Pacific Ocean, consistent with the uniform aerosol and cloud microphysical environment over this region.

CHAPTER THREE

3.0 METHODOLOGY

In order to record lightning activity over the study area, a lightning sensor was designed (Figure 3.1). This differs from the conventional lightning sensors (VHF, VLF and ELF lightning sensors) in that it operates around a frequency of 300 kHz which lies between the VLF (3-30 kHz) [Pierce, 1977] and VHF frequency bands. Though lightning generates a broad band of frequency range, almost all types of lightning discharge (cloud-to-ground, cloud-to-cloud and intra-cloud) can be found around this frequency (300 kHz). Therefore, cloud-to-ground, cloud-to-cloud and intra-cloud lightning discharge can all be detected using this lightning sensor.

3.1 The lightning sensor and its theory of operation

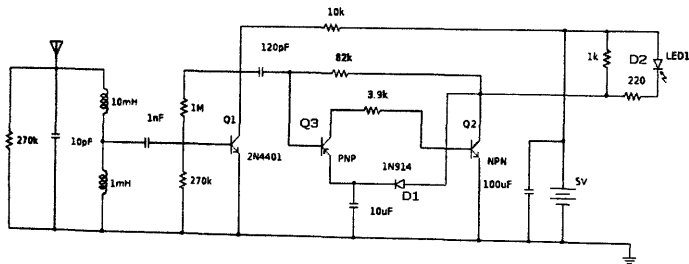


Figure 3.1: Circuit for the lightning sensor design. (Adapted from Tech. Library, 2006).

Lightning flashes generate a broad spectrum of radio frequencies with especially intense emissions in the VLF band. This receiver is designed to pick up a band near 300 kHz

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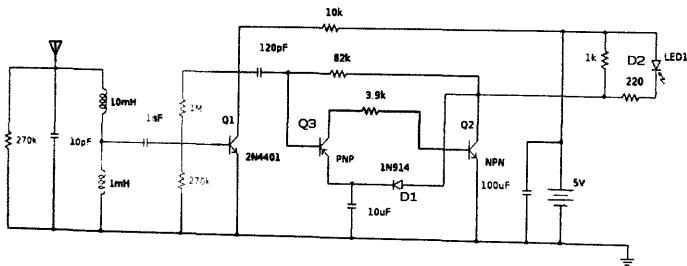


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Lightning flashes generate a broad spectrum of radio frequencies with especially intense emissions in the VLF band. This receiver is designed to pick up a band near 300 kHz

which is fairly empty except for lightning static. These radio "crackles" are picked up by the antenna with the help of the 10 pF capacitor, and the two inductors which form a resonant tank at about 300 kHz, a good frequency for receiving energy from lightning. The two series inductors act as a matching network, feeding Q1 with a lower impedance version of the signal received by the antenna. The 270 k Ω resistor lowers the Q (high pulse) of the resonant tank to prevent oscillation. Q1 amplifies the 300 kHz bursts and applies the larger signal to the base of Q3 (PNP transistor) that forms a mono-stable "flasher" circuit with the last NPN transistor (Q2). When the RF signal pulls the PNP base voltage below the voltage on the 10 μ F capacitor (plus about 0.6 volts) the PNP turns on, turning on the NPN. Since the NPN is connected to the base of the PNP through the 82 k Ω resistor, the PNP turns on even harder. This regenerative action causes the circuit to turn on quickly and fully, pulling the "pulses" line to nearly zero volts. The circuit stays on until the 10 μ F capacitor discharges, at which point a similar reverse regenerative action causes the circuit to quickly switch off. The capacitor then quickly charges through the 1 k Ω resistor and the diode and is ready for another pulse.

To complete the circuit, a light sensor was mounted over the Light Emitting Diode (LED) which records the light intensity as a result of the pulse generated voltage in the circuit by the lightning discharge. The intensity of the light emitted by the LED is proportional to the actual lightning intensity.

To ensure that the constructed sensor was working according to specifications, a simple R-C spark generator (Figure 3.2) was designed to mimic lightning in the lab in order to test the lightning sensor. The circuit basically consists of DC power supply with a

maximum output of 12 V, a condenser (a capacitor: $0.47\ \mu\text{F}$, $0.03\ \Omega$), a car ignition coil, a tab key and a spark gap as indicated in the figure.

By steadily increasing the input voltage to the maximum 12V, a maximum spark gap of 2.5cm was obtained. The spark produced by this generator was very weak so the detector was only able to pick about 2 out of every 10 sparks generated.

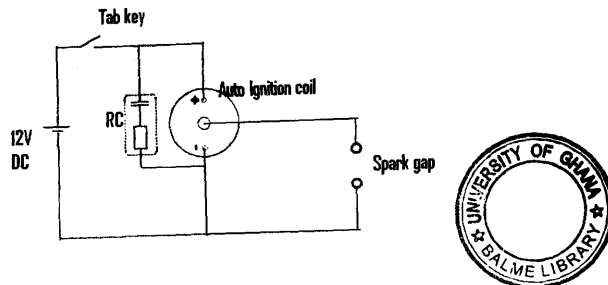


Figure 3.2: Circuit for the spark generator used to test the lightning sensor.

3.2 Data Collection

Two parameters were studied during this work, lightning intensity and the amount of rainfall (precipitation). Temperature was not considered because in studying lightning, cloud temperature is used instead of the ambient temperature.

Lightning data was obtained in the Department of Physics using the designed lightning sensor whereas rainfall figures were obtained from the Meteorological garden of the Department of Geography and Resource development a distance of about 300 m from the

Physics department. However, a few of the rainfall figures were also obtained from the Menpeasem station of the Ghana Meteorological Agency a distance of about 5 km from the study site.

The Time of Arrival (TOA) method was employed in this project. This involves recording the light intensity measured by the light sensor and the corresponding time the lightning occurred. The amount of rainfall measured during the entire duration of the thunderstorm was also recorded.

Data was collected for a period of approximately two and a half months and the result obtained is presented in next chapter of this report.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

In this chapter, the results obtained from the observations of the total lightning activity (including cloud-to-ground, cloud-to-cloud and intra-cloud) together with the other environmental parameters (including total amount of rainfall over the duration of the thunderstorm activities and relative humidity during the thunderstorms) over the Legon campus are presented and thoroughly analyzed to ascertain possible relationships between them.

4.1 Lightning activities

Figure 4.1 through to Figure 4.18 represent the lightning activity during the period of observation from the months of May to July. The vertical axes represent the light intensities recorded by the light sensor (in watt per square meter), which is proportional to the lightning intensity. The horizontal axes give the time of arrival of the lightning strike at the observation station.

The first trend that was observed was that, thunderstorms producing light intensities above 60 Wm^{-2} were associated with moderate to heavy rainfall whilst thunderstorms producing light intensities below 60 Wm^{-2} were associated with slight drizzle or rain. Another trend observed was that, the higher the number of lightning strikes, the higher the amount of rainfall during a typical thunderstorm day.

Figure 4.3 gives the maximum thunderstorm activity recorded (a total of 200 lightning strikes) and also produced the highest rainfall amount (117.3 mm) in less than 3 hrs. This

resulted in flooding around Legon and some parts of Accra. Some communication industries (particularly Mobile Telecom Network, MTN) experienced problems with some of their transmission equipment as a result of the massive lightning strikes that night. This can be seen from the chart having large number of peaks closely packed together as compared to the other charts.

Thunderstorm activity which occurred on May 24, 2008 (Figure 4.5) had no rain associated with it though it was cloudy and windy that day. Although some rains do not have lightning strikes associated with them (rains from nimbostratus clouds), none had been recorded as at the time of writing this report.

From these observations, it can be seen that the month of May recorded the highest amount of rainfall with an average of 28.5 mm of rain and an average of 74 lightning strikes per thunderstorm. The month of June had an average of 9.1mm of rain per thunderstorm and an average of 45 lightning strikes per thunderstorm. For the month of July, due to the time constraint of this work, only one reading was obtained on July 2, 2008 (23.8 mm of rain, 56 lightning strikes).

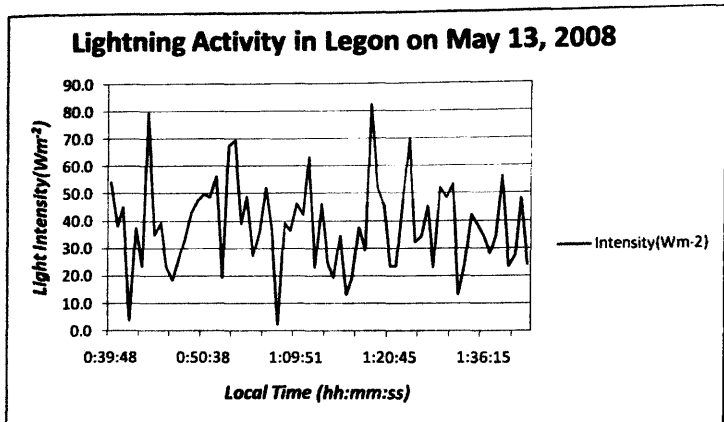


Figure 4.1: Lightning activity recorded on the University of Ghana campus on May 13, 2008.

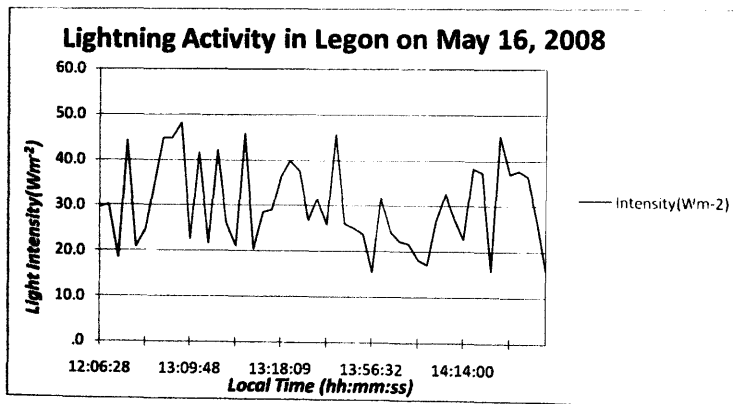


Figure 4.2: Lightning activity recorded on the University of Ghana campus on May 16, 2008.

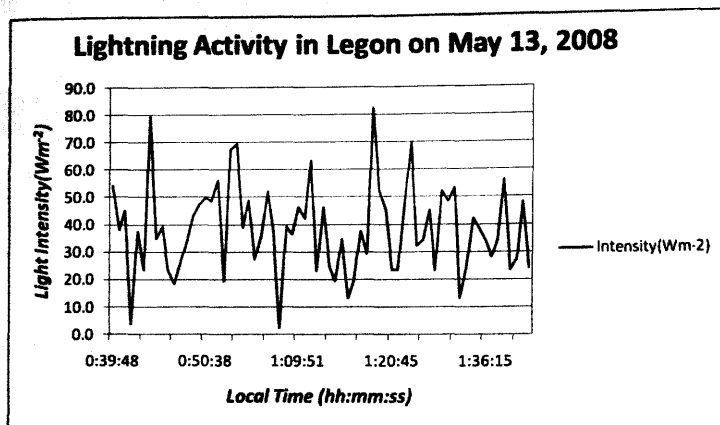


Figure 4.1: Lightning activity recorded on the University of Ghana campus on May 13, 2008.

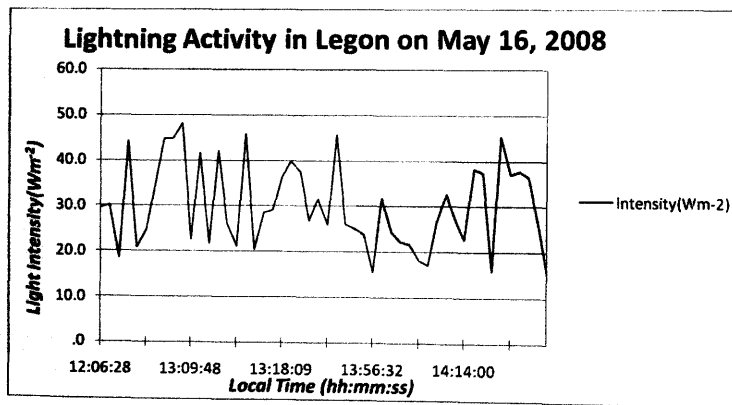


Figure 4.2: Lightning activity recorded on the University of Ghana campus on May 16, 2008.

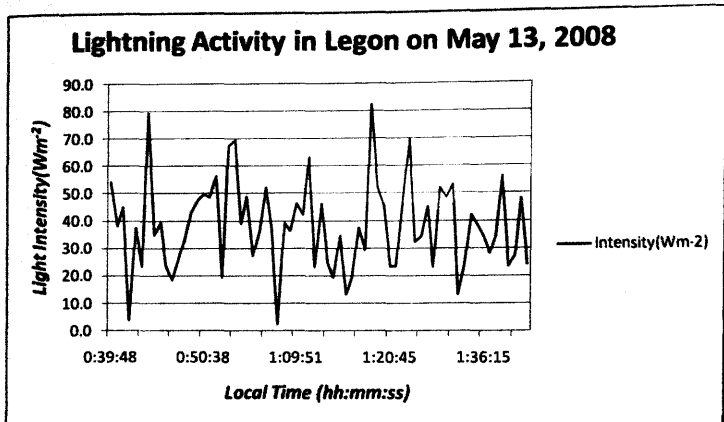


Figure 4.1: Lightning activity recorded on the University of Ghana campus on May 13, 2008.

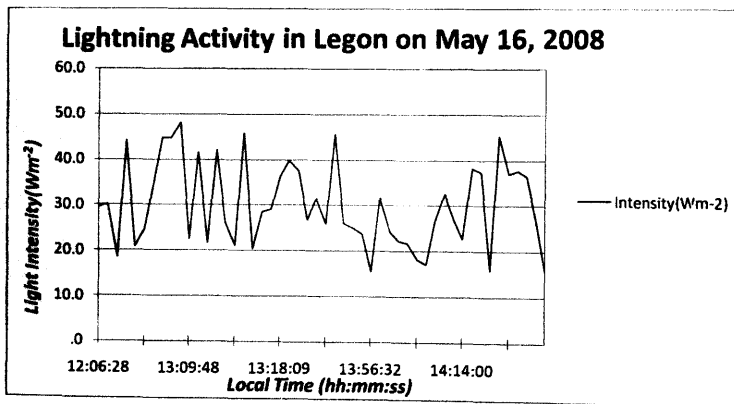


Figure 4.2: Lightning activity recorded on the University of Ghana campus on May 16, 2008.

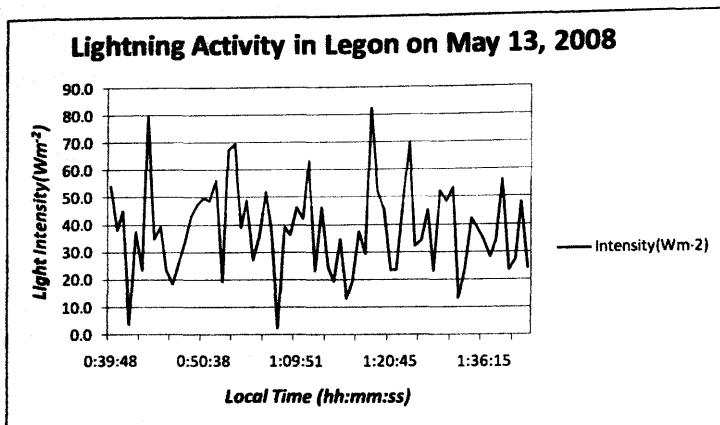


Figure 4.1: Lightning activity recorded on the University of Ghana campus on May 13, 2008.

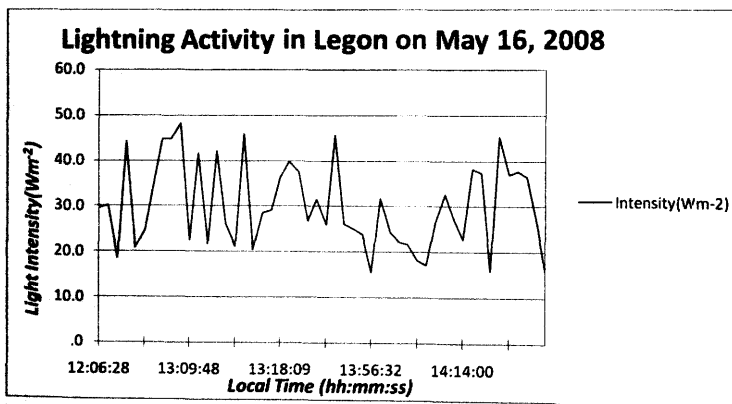


Figure 4.2: Lightning activity recorded on the University of Ghana campus on May 16, 2008.

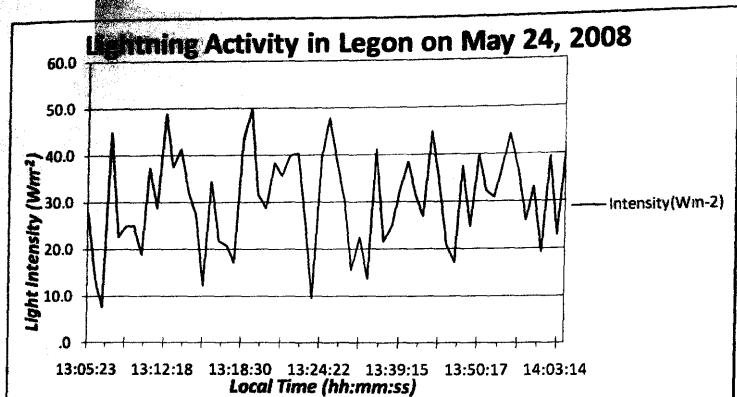


Figure 4.5: Lightning activity recorded on the University of Ghana campus on May 24, 2008.

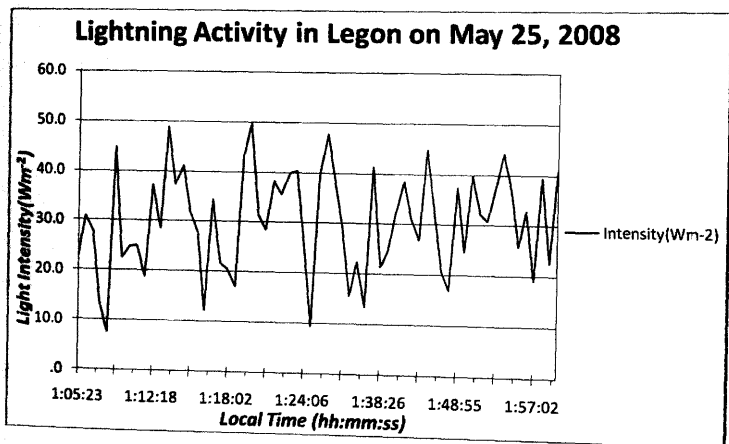


Figure 4.6: Lightning activity recorded on the University of Ghana campus on May 25, 2008.

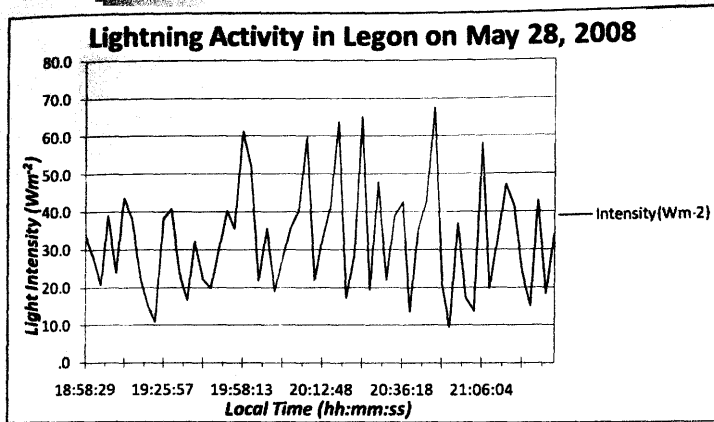


Figure 4.7: Lightning activity recorded on the University of Ghana campus on May 28, 2008.

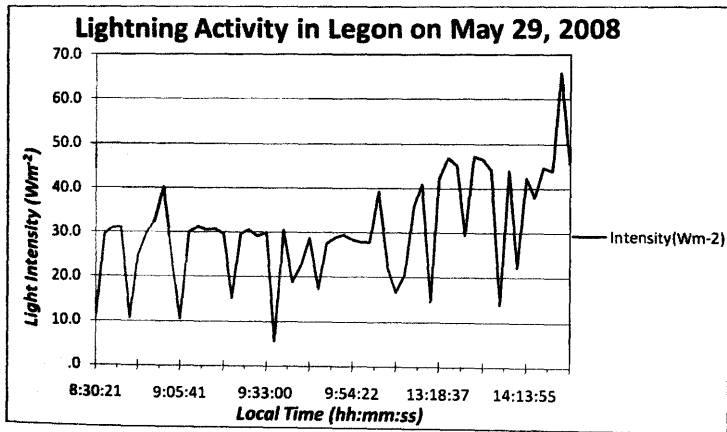


Figure 4.8: Lightning activity recorded on the University of Ghana campus on May 29, 2008.

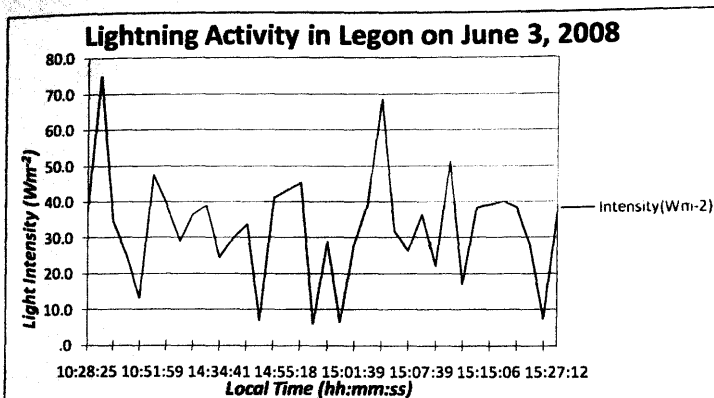


Figure 4.9: Lightning activity recorded on the University of Ghana campus on June 3, 2008.

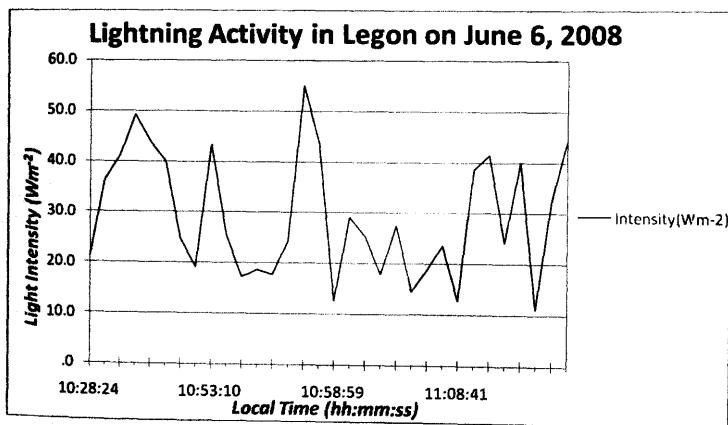


Figure 4.10: Lightning activity recorded on the University of Ghana campus on June 6, 2008.

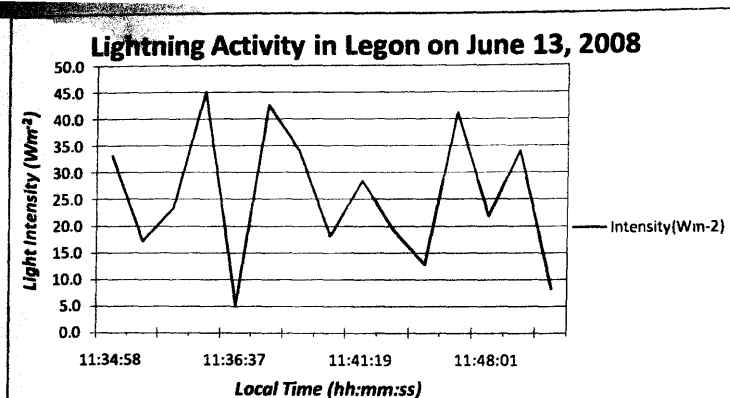


Figure 4.11: Lightning activity recorded on the University of Ghana campus on June 13, 2008.

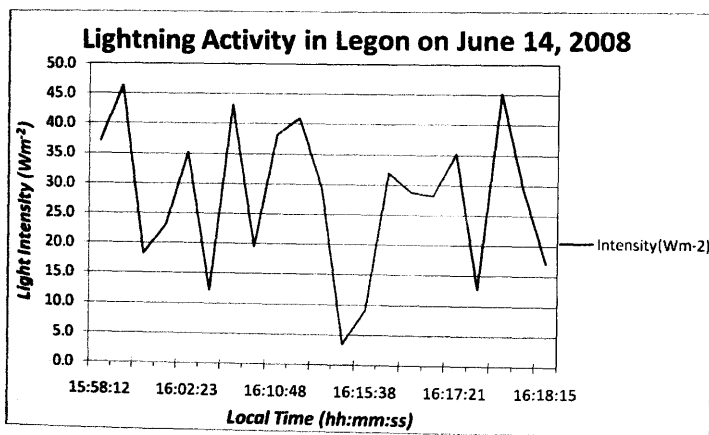


Figure 4.12: Lightning activity recorded on the University of Ghana campus on June 14, 2008.

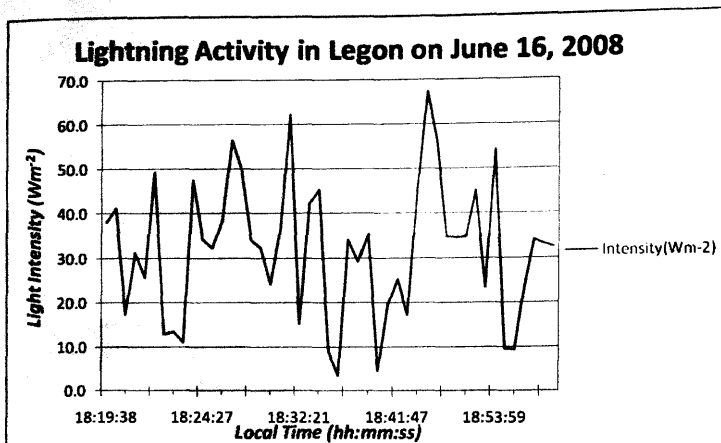


Figure 4.13: Lightning activity recorded on the University of Ghana campus on June 16, 2008.

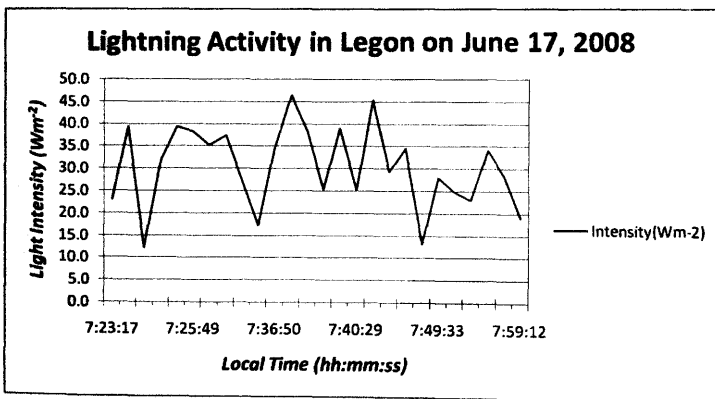


Figure 4.14: Lightning activity recorded on the University of Ghana campus on June 17, 2008.

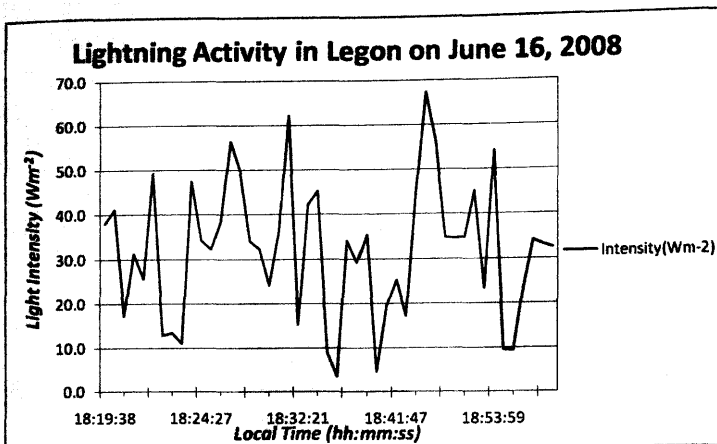


Figure 4.13: Lightning activity recorded on the University of Ghana campus on June 16, 2008.

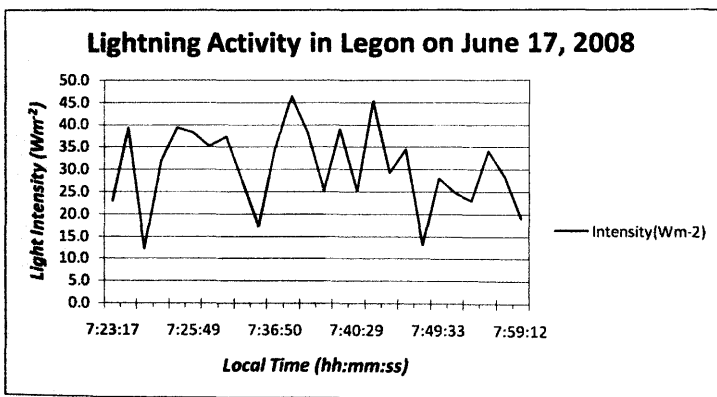


Figure 4.14: Lightning activity recorded on the University of Ghana campus on June 17, 2008.

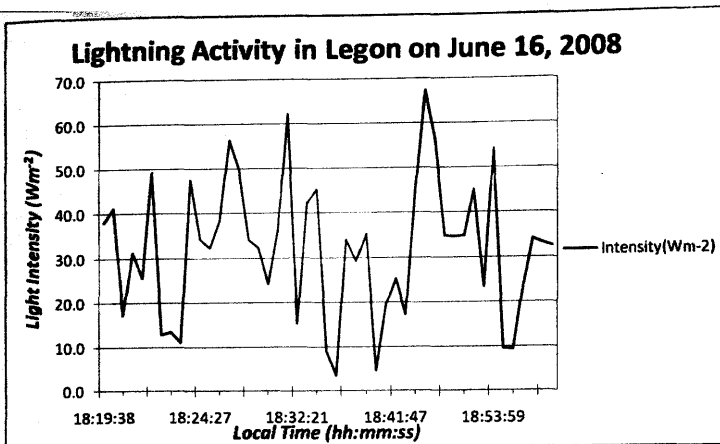


Figure 4.13: Lightning activity recorded on the University of Ghana campus on June 16, 2008.

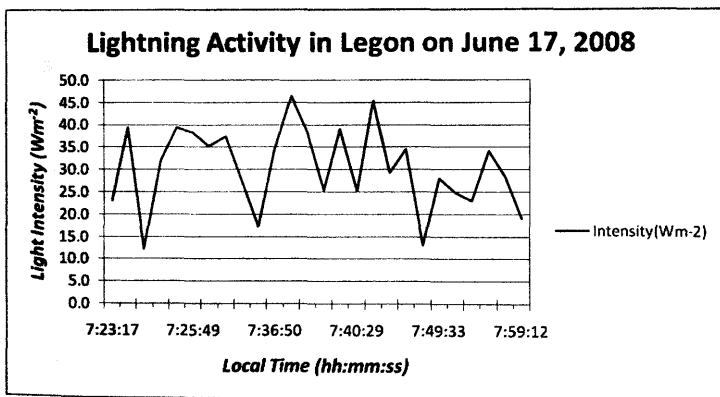


Figure 4.14: Lightning activity recorded on the University of Ghana campus on June 17, 2008.

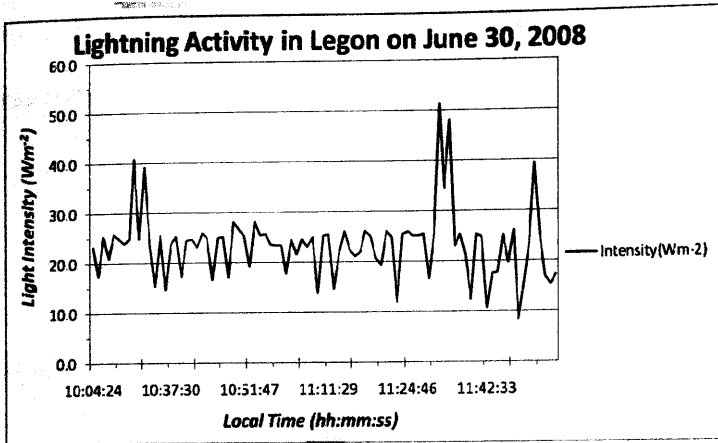


Figure 4.17: Lightning activity recorded on the University of Ghana campus on June 30, 2008.

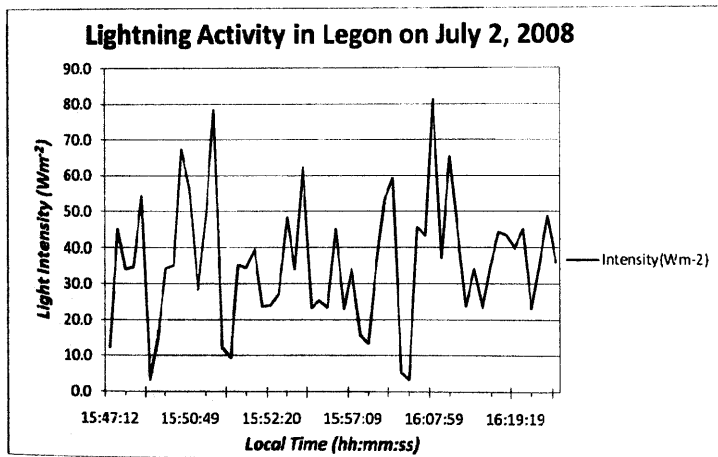


Figure 4.18: Lightning activity recorded on the University of Ghana campus on July 2, 2008.

4.2 Making a visual comparison between lightning strikes and rainfall figures

Figure 4.19 below compares the total number of lightning strikes (including cloud-to-ground, cloud-to-cloud and within cloud lightning) to the amount of rainfall during the period under study. The dark bars represent the total number of lightning strikes; the lighter bars represent the amount of rainfall in millimeters.

As stated in the third paragraph of section 4.1, a general trend of increasing number of lightning strikes has a corresponding increase in the amount of rainfall. This can clearly be seen on Figure 4.19.

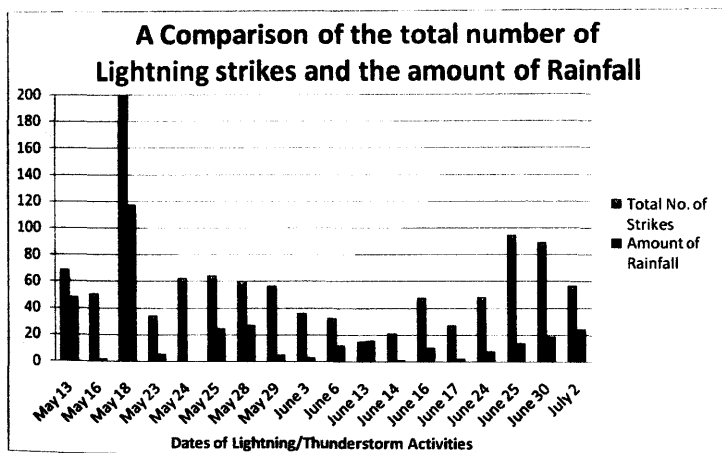


Figure 4.19: A bar chart comparing the total number of lightning strikes to the amount of rainfall for the various days with thunderstorm activity on the University of Ghana campus.

Figure 4.20 below is a representation of the lightning flash rate per hour (obtained by dividing the total lightning strikes by the duration of the thunderstorm in hours) and the rainfall amount on a bar chart. The flash rate is represented by the dark bars with the lighter bars representing the amount of rainfall.

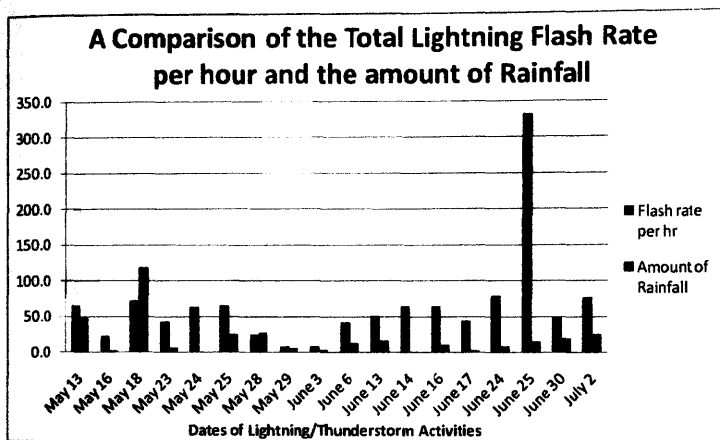


Figure 4.20: A bar chart comparing the lightning flash rate per hour and the amount of rainfall recorded over the period of observation.

4.3 Relationship between lightning activities and the amount of rainfall

Scatter plots between the amount of rainfall and the total lightning strikes were generated and are presented in Figures 4.21 to 4.26. There is considerable amount of scatter between the amount of rainfall and the total lightning strikes. As a result of this, various

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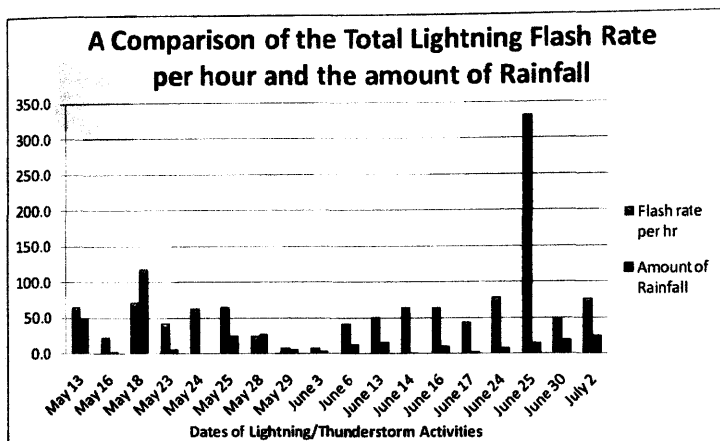


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degrees of curve fitting were performed on the scatter plot in order to obtain an acceptable and reasonable relationship between the amount of rainfall and the total lightning strikes.

In the very first case, a linear regression line was obtained with an equation of $y = 0.5782x - 15.5$ where y represents the amount of rainfall and x represents the total lightning strikes during the thunderstorm (Figure 4.21). However, a corresponding value of the square of the correlation coefficient r^2 was obtained as 0.7462. This value according to Bluman, indicates a strong linear relationship between the amount of rainfall and the total number of lightning strikes [Bluman, 2004].

In the second case, a quadratic curve was fitted to the scatter plot of rainfall figures and the number of lightning strikes (Figure 4.22).

A relationship of $y = 0.0031x^2 - 0.065x + 6.851$ was obtained with a r^2 value of 0.8295.

Subsequent polynomial curve fittings of degree 3 to 6 recorded a steady increase in the r^2 values until degree 6 where a maximum r^2 value of 0.895 was obtained with a corresponding polynomial equation of obtained as $y = 2E-09x^6 - 8E-07x^5 - 0.007x^3 + 0.252x^2 - 5.132x + 51.53$.

Looking at the square of the correlation coefficient values for graphs 4 to 6, it is clear that their equations would be good rainfall figure estimators. However, they are not suitable for the following reason. Upon studying these graphs closely, it will be noted that whenever the total number of lightning strikes exceeds 95, negative rainfall values are obtained and this is not practically true.

The equation obtained for Figure 4.23 ($y = 2E-05x^3 - 0.0037x^2 + 0.4287x - 2.3078$) is the best option when it comes to rainfall figure estimation if it is assumed that all rainfall will have some lightning activity and that the number of lightning strikes does not exceed 200. The negative part of this graph can be ignored without loss of generality since it is unrealistic to have thunderstorms with less than 10 lightning strikes

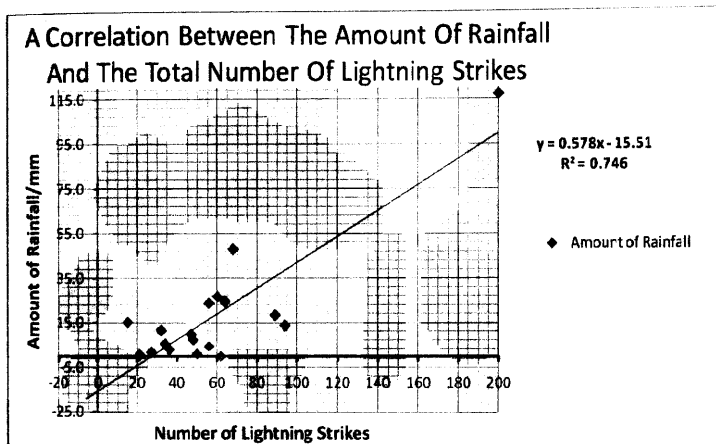


Figure 4.21: A linear regression between the amount of rainfall and the total number of lightning strikes.

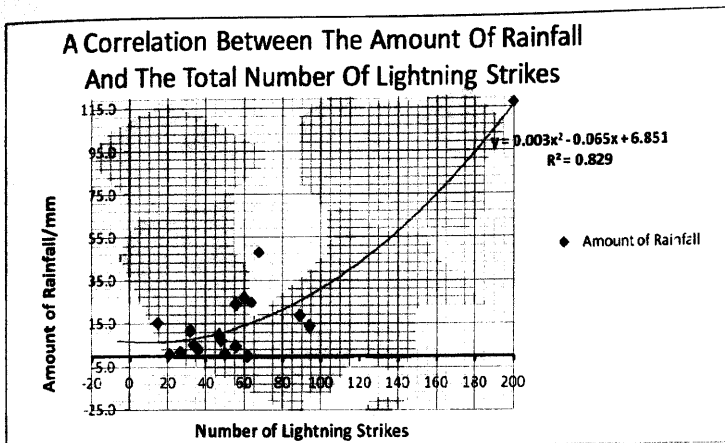


Figure 4.22: A polynomial regression of the second order between the amount of rainfall and the total number of Lightning strikes.

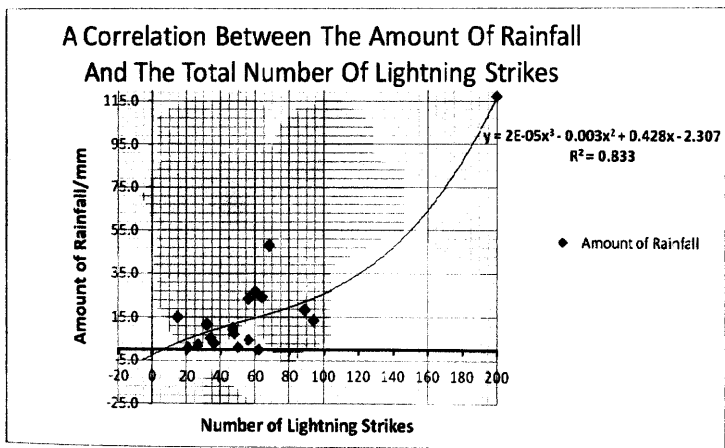


Figure 4.23: A polynomial regression of the third order between the amount of rainfall and the total number of Lightning strikes.

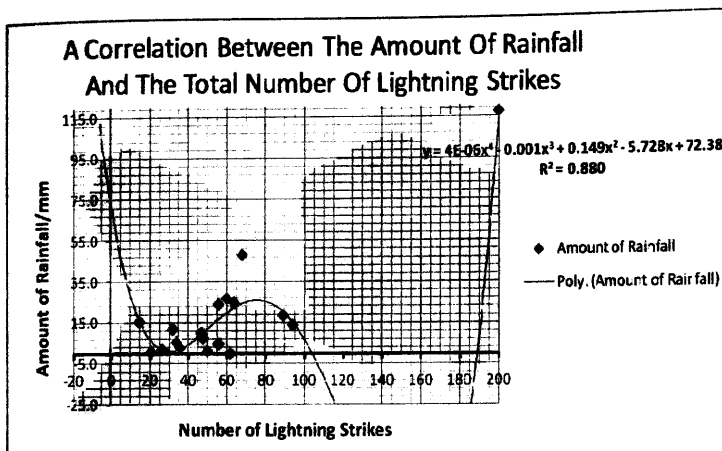


Figure 4.24: A polynomial regression of the fourth order between the amount of rainfall and the total number of Lightning strikes.

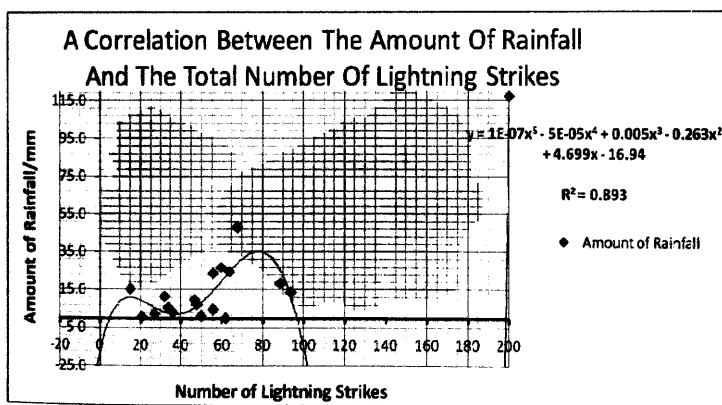


Figure 4.25: A polynomial regression of the fifth order between the amount of rainfall and the total number of Lightning strikes.

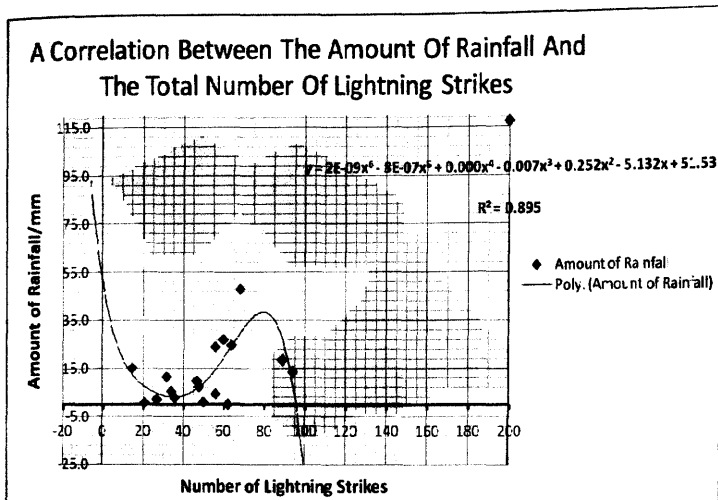


Figure 4.26: A polynomial regression of the sixth order between the amount of rainfall and the total number of Lightning strikes.

Similarly, various degrees of curve fittings were performed between the amount of rainfall and the lightning flash rate (obtained by dividing the total number of lightning strikes by the duration of the thunderstorm in hours) and unlike the fitting between rainfall figures and the number of lightning strikes, no observable relationship was obtained (figure 4.27 to figure 4.31).

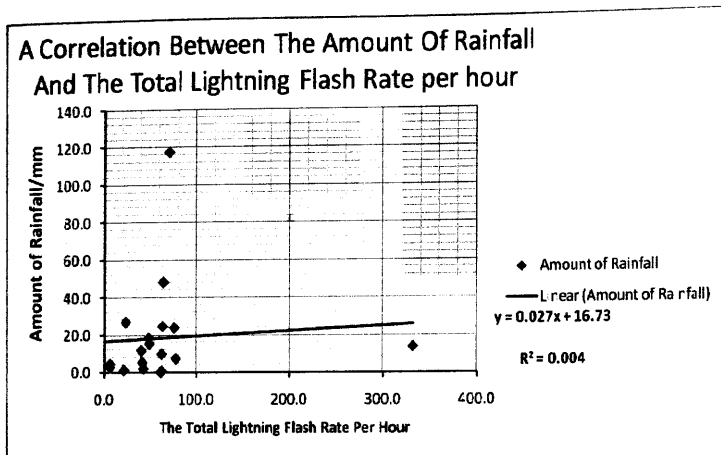


Figure 4.27: A linear regression between the lightning flash rate per hour and the amount of rainfall and the Lightning flash rate per hour.

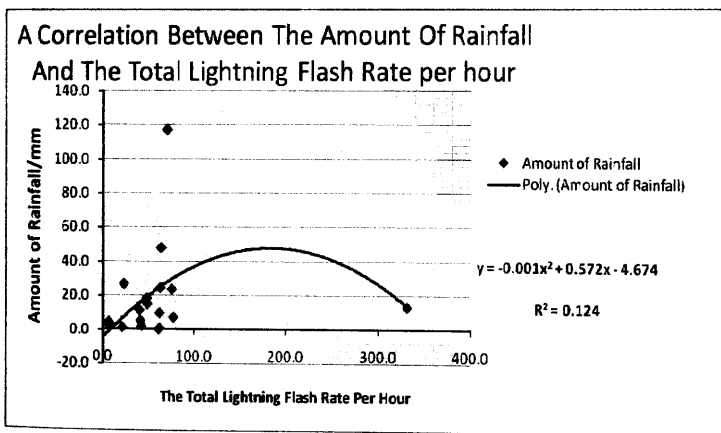


Figure 4.28: A polynomial regression of the second order between the amount of rainfall and the Lightning flash rate per hour.

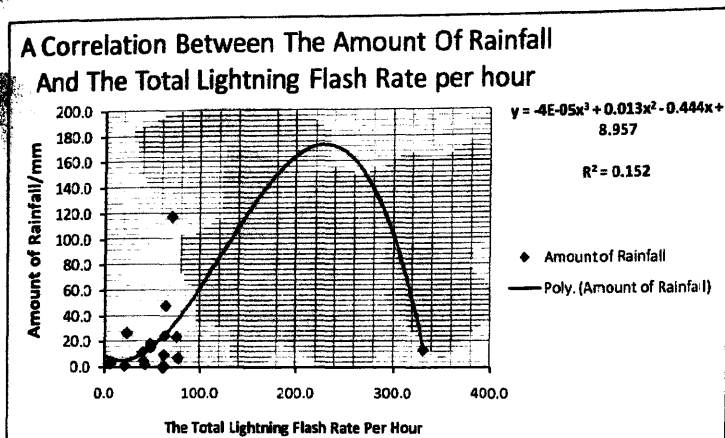


Figure 4.29: A polynomial regression of the third order between the amount of rainfall and the lightning flash rate per hour.

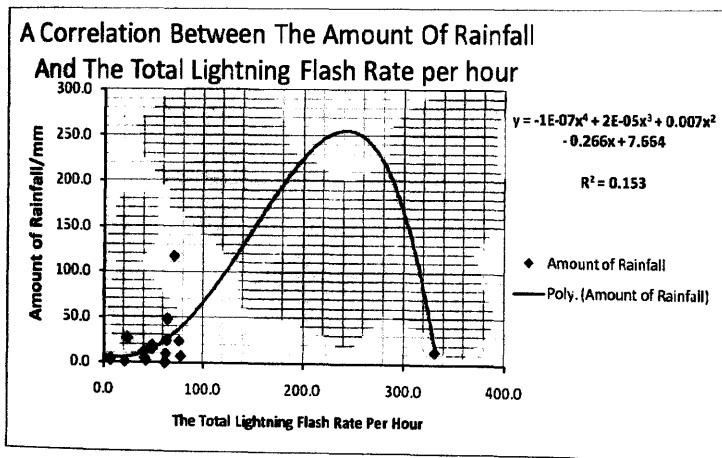


Figure 4.30: A polynomial regression of the fourth order between the amount of rainfall and the lightning flash rate per hour.

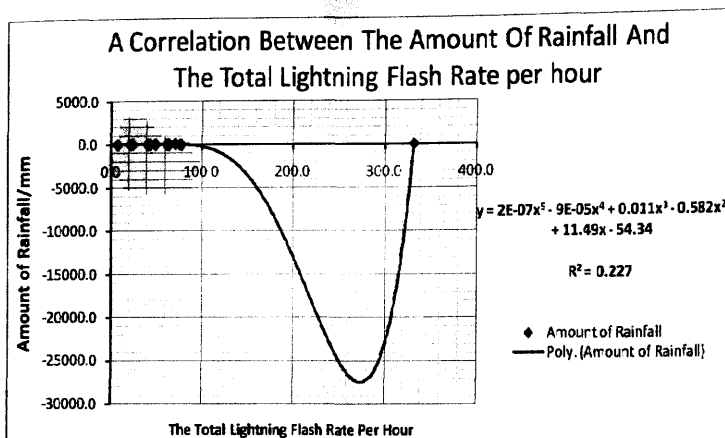


Figure 4.31: A polynomial regression of the fifth order between the amount of rainfall and the lightning flash rate per hour.

4.4 Comparing this work to other related works

Preliminary results from this work show that higher number of lightning strikes in a thunderstorm is accompanied by heavy rainfall amount. This observation is consistent with the results obtained by Pessi *et. al.*, (2004).

The results also indicate that the ratio of lightning strikes to rainfall depends greatly on the type of cloud producing the rainfall. If the same amount of rainfall is produced by nimbostratus clouds and cumulonimbus clouds, much more lightning strikes were recorded in the cumulonimbus clouds (that is, intense precipitation can develop without subsequent electrification but appreciable cloud electrification is invariably accompanied

However, the weak correlation between the lightning flash rate and the amount of rainfall can be attributed to the fact that some thunderstorms last relatively longer than others without necessarily producing more rainfall.

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CHAPTER FIVE

5.0 CONCLUSIONS AND SUMMARY

After making a thorough analysis of the lightning and rainfall data, the following conclusions can be drawn.

The total number of lightning strikes (x) is correlated ($r^2 = 0.8332$) to the amount of rainfall (y) by the cubic equation, $y = 2E-05x^3 - 0.0037x^2 + 0.4287x - 2.3078$. Hence this equation can be used to estimate the amount of rainfall during a thunderstorm if the number of lightning strikes is known. However there was no correlation between the lightning flash rate and the amount of rainfall.

The maximum number of lightning strikes recorded during the study period was 200 ± 1 and this occurred on May 18, 2008; on that night most parts of Accra were flooded. Also a minimum of 16 ± 1 lightning strikes was also recorded during this same period which also occurred on June 13, 2008.

A maximum light intensity of $84.8 \pm 0.1 \text{ Wm}^{-2}$ was recorded on June 25, 2008 at 11:39:29 local time. A minimum of $1.3 \pm 0.1 \text{ Wm}^{-2}$ was recorded on May 18, 2008 at 20:07:16 local time.

Rainfall figures recorded over the period of study had a maximum value of $117.3 \pm 0.1 \text{ mm}$ which also occurred on the day of flooding (May 18, 2008). However no rain was recorded on May 24, 2008 though there were thunderstorm activities.

5.1 Recommendations

An appropriate data logger must be used when replicating this work as this will make the lightning detection automatic. In addition, an alarm system can also be included in the circuit in order to be alerted when lightning strikes for the very first time during a thunderstorm.

For an effective lightning detection, more sensors must be constructed and positioned a distance of about 10 km from each other by triangulating them to form a network. By using Pythagoras theorem, the exact direction of a lightning strike can be determined if each station records the time between the lightning flash and the thunder.

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