

Electromagnetic Storm in the Atmosphere: Magnetic Induction Field and Electric Current Density Generated by the Cumulonimbus Cloud Observed in Chad

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Abstract

The study of electromagnetic phenomena in the atmosphere is very interesting because it allows us to predict the dangers caused by induced currents resulting from an electrical discharge from an existing cumulonimbus cloud. Simulation of the electromagnetic properties of a possible discharge from the cumulonimbus cloud observed in Chad shows that lightning can occur with a very high magnetic field intensity and an electric current density outside safe limits. Such an electrical discharge could not occur without consequences for the surrounding electrical equipment, the habitat, and humanity.

Keywords

Storm, Current Density, Lightning, Electric Field, Magnetic Field

1. Introduction

Clouds play an essential role in meteorology and climatology. The shape of clouds depends on the environment in which they form, according to the mechanism of condensation of water from seas and oceans that evaporate [1]. They depend on updrafts at varying temperatures and humidity levels, which explains why clouds can take on fascinating appearances that can change shape and even disappear over time [2].

When observing lightning strikes, electrical charges are generated not only by

nimbostratus clouds, but also by cumulonimbus clouds. However, 80% of electrical discharges originate from nimbostratus clouds [3] and [4]. In the literature, few theories describe both the qualitative and quantitative aspects of phenomenon occurs in nimbostratus clouds; however, a number of theoretical models adequately describe the phenomena of discharges occurring in cumulonimbus clouds.

Lightning can be defined as a natural phenomenon involving electrical discharges that can occur when a large amount of static charge accumulates in areas of storm clouds. It is a common phenomenon that acts as a perfect generator of electrical current. In the context of climate change, extreme weather events [4] such as thunderstorms accompanied by lightning are occurring with increasing frequency, causing enormous damage to infrastructure. These electrical discharge phenomena, resulting from the presence of cumulonimbus clouds in a given region [4] and [5], have long remained a mystery to most people and pose a danger to living beings, energy infrastructure, homes, and much more [5].

Lightning is a natural phenomenon involving an electrical discharge that occurs when the potential difference between two neighboring storm clouds or between a cloud and the ground generates an electrostatic field equal to or greater than the average value $E(d) = 10^6 \text{v.m}^{-1}$ (disruptive field) in humid air. This disruptive field is responsible for ionizing the surrounding air molecules and forming a conductive medium conducive to the movement of electrical charges, which can potentially cause lightning strikes. These strikes have adverse consequences on the energy distribution networks on which most human activities depend [6]. To limit extensive damage to electrical equipment, surge protectors using various technologies have been designed. These are electrical protection devices designed to limit power surges, particularly those caused by lightning, and protect electrical equipment from damage [7] and [8]. During operation, surge arresters divert the surge current to the ground, preventing it from reaching electrical equipment and causing breakdowns or fires on distribution lines.

In references [9] and [10], the authors analyzed the effects of lightning and its coupling to the electrical grid. It appears that despite the efforts made by researchers, the complexity of lightning and its accompanying effects remain fertile ground for further study and require work to ensure reliable protection for electrical systems. In order to minimize the effects of lightning during electrical discharges [11], the author proposed a mathematical model that could protect against the harmful effects of power surges caused by electrical discharges that could potentially lead to the formation of lightning. The modeling of atmospheric electrical discharges and the design and dimensioning of lightning protection systems were the subject of Paulino's publication [12]. It shows that for very high soil resistance, the potential generated by an atmospheric electrical discharge (lightning) drained to the ground can exceed safety limits, causing adverse consequences for distribution networks and human activities. To protect distribution networks from the harmful effects of lightning, algorithms and methods for opti-

mizing protection systems were simulated in the work of Zhong *et al.* [13]. Their approach consists of optimizing the performance of a current-interrupting surge arrester on a distribution network through the use of a binary particle. Knowing that the cumulonimbus clouds causing these discharges are characterized by physical parameters that are dynamic in time and space, Khodsuz *et al.* [14] show that the design of a dynamic variable lightning arrester, equipped with a metal oxide switch, allows for significant attenuation of the leakage current caused by imperfections in the various components of the distribution chain. Such a surge arrester is an effective means of protecting against the power surges caused by these discharges. By using zinc oxide as a switch, the surge arrester used in the work of Zhou *et al.* [15] reduces the voltage to below its minimum value, known as the surge voltage, without causing any adverse effects on the distribution lines of the electrical network in question. This research shows that metal oxide surge arresters offer better performance in protecting high-voltage electrical distribution networks and limit the magnetic effects induced by the movement of charges in the ionized medium. A comparative study of various cases of lightning strikes on distribution lines and an assessment of the level of protection against surges caused by these discharges were the subject of a study by Aida *et al.* [16]. They show that the electromagnetic effects caused by the displacement of charges cause surges and induced currents that exceed safety limits. As for the performance of various types of surge arresters, the results show that a higher level of protection against the effects of lightning requires a combination of a surge arrester with a current switch and the use of a lightning rod-type surge arrester.

Located in the heart of Africa between 7° and 24° north latitude, 13° and 24° east longitude, Chad has a generally tropical climate that varies from north to south depending on latitude, ranging from a dry desert climate in the north to a Sahelian climate in the center and finally to a more humid Sudanese climate in the south, with two main seasons. In its tropical and Sahelian climate zones, storm clouds able of generating lightning are common. Unfortunately, weather forecasts rarely, if ever, mention the presence of cumulonimbus and nimbostratus clouds responsible for lightning strikes or simple electrical discharges. In addition, in Chad's higher education programs, little attention is given to the study of electrical discharge phenomena in the atmosphere. In light of the above-mentioned studies reporting the harmful effects of lightning caused by the discharge of a cumulonimbus or nimbostratus cloud, we are concerned about whether the magnetic field and current density induced by the electromagnetic effects characterizing the cumulonimbus cloud observed on July 16, 2021, in Chad, are not likely to produce the effects of lightning, as reported in previous studies? This paper, which aims to provide an analytical and numerical study of the effect of the cumulonimbus cloud observed at Hassan Djamous International Airport, will be structured as follows: In the second section, we will discuss the materials and methods used to study this phenomenon. In the third section, we will discuss our results and compare them with those found in the literature review on the subject. We will

conclude this manuscript with a conclusion.

2. Materials and Methodology

2.1. Materials

In terms of equipment, we used MATLAB software to plot the variation curves of the electric and magnetic fields and the current density induced by the movement of charges in the cumulonimbus cloud observed in Chad. In addition to MATLAB software, we used the aerological diagram for July 16, 2021, obtained at Hassan Djamous International Airport in N'Djamena (source: ASECNA), see **Figure 1**. To simulate the expressions of the electric field $E(z)$, magnetic field $B(z)$, and corresponding current density $j(z)$, we worked under the assumption of reference

$$[17] \text{ for which } \rho_m = \rho_{sol} = \rho_0 = \frac{1.0 \times 10^{-9} \text{ C}}{m^3}.$$

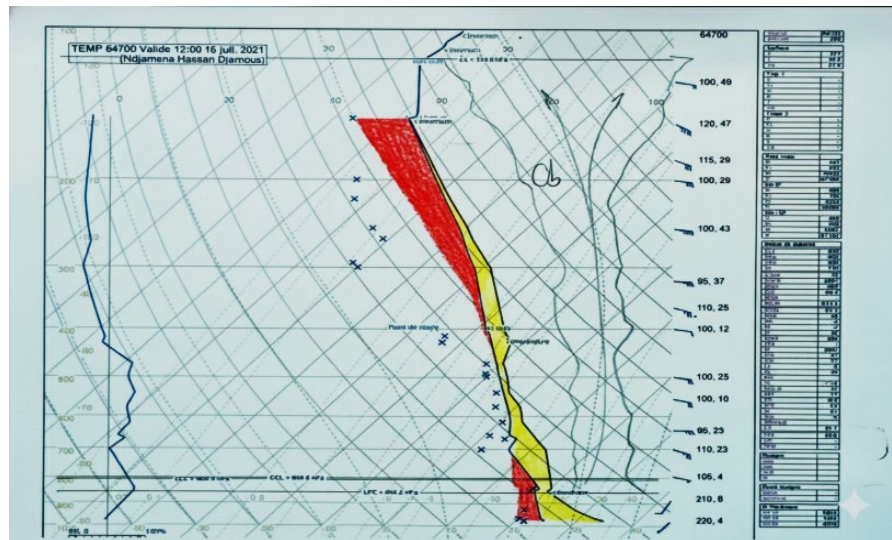


Figure 1. Aerological diagram observed on July 16, 2021, at Hassan Djamous International Airport in N'Djamena (source: ASECNA). On this diagram, the intersection of the air temperature variation curves and the dew point variation curves gives the top of the cumulus nimbus cloud at altitude z_3 . The base of the cloud z_2 is located at the intersection of the temperature variation curves and the mixture ratio curves. At low altitudes, the intersection of the dry adiabatic curves with the temperature curves gives the altitude z_1 of the city of N'Djamena.

2.2. Methodology

Our methodological approach consists of using the local form of Gauss's theorem [18] to determine the electric field characterizing the cumulonimbus cloud observed in Chad. This would allow us to know whether this cloud would result in a simple electrical discharge or a lightning strike. Since temperature varies linearly with altitude in the atmosphere, charge density, which is in turn a function of temperature, will have a linear dependence on the altitude at which the cloud is located [19]. In the aerological diagram in **Figure 1**, the volume density $\rho(z)$ is a function that varies linearly with altitude according to the relationship:

$$\rho(z) = Az + B \tag{1}$$

Where A and B are two constants to be determined. On the diagram, $z_1 = 295$ m, $z_2 = 1.3$ km, and $z_3 = 15.3$ km represent the altitude of the city of N'Djamena, the altitude of the base of the cumulonimbus cloud, and the altitude of the top of the cloud, respectively.

Knowing that $\rho(z_1) = -\rho_0$ and $\rho(z_2) = \rho_0$, the variation in charge density $\rho(z)$ gives the system of equations

$$\begin{cases} -\rho_0 = B + Az_1 \\ \rho_0 = B + Az_2 \end{cases} \tag{2}$$

whose resolution gives the expressions of the constants

$$A = \frac{2\rho_0}{z_2 - z_1} \tag{3}$$

et

$$B = -\frac{A}{2}(z_1 + z_2) \tag{4}$$

The charge density $\rho(z)$ in the cumulonimbus cloud will be given by:

$$\rho(z) = \frac{2\rho_0}{H}(z - (z_1 + z_2)), \tag{5}$$

With $H = z_2 - z_1$. Integration in space of the local form of Gauss's theorem

$$\text{div}\mathbf{E}(z) = \frac{\rho(z)}{\epsilon_0} \tag{6}$$

gives the field inside the cumulonimbus cloud at altitude z , expressed as

$$E(z) = \frac{\rho_0}{\epsilon_0 H}(z^2 - (z_1 + z_2)z) + C, \tag{7}$$

Where C is an integration constant whose value will be determined. Taking into account the continuity of the field between the two altitudes z_1 and z_2 , expressed as $E(z_1) = E(z_2)$, we obtain the expression for the constant

$$C = \frac{1}{\epsilon_0} \left(\rho_{sol} z_1 + \frac{\rho_{mz_1 z_2}}{H} \right). \tag{8}$$

The electric field inside the cloud can therefore be written as:

$$E(z) = \frac{\rho_0}{\epsilon_0 H}(z^2 - (z_1 + z_2)z) + \frac{1}{\epsilon_0} \left(\rho_{sol} z_1 + \frac{\rho_{mz_1 z_2}}{H} \right). \tag{9}$$

Equation (9) quantifies the intensity of the electrostatic field created by static charges in the cloud located at altitude z above the ground. As they discharge toward the ground, they create a magnetic induction field during their movement, which is linked to the electrostatic field by Maxwell-Faraday's equation [18]:

$$\text{rot}\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t} \tag{10}$$

The Maxwell-Faraday equation postulates that if the B field varies over time,

the E field cannot be zero. The immediate consequence of this postulate is that the electric and magnetic fields can no longer be studied separately: the electromagnetic field is referred to as a single entity. Integrating equation (10) gives, by virtue of Equation (9), the intensity of the magnetic field produced by the displacement of the charges in the cloud.

$$B(z, t) = \frac{\rho_0}{\epsilon_0 H} (2z - (z_1 + z_2)t) + \alpha \quad (11)$$

Taking into account the fact that before the cloud discharges, the magnetic field is zero due to the absence of movement, considering this boundary condition in the equation (11) gives $\alpha = 0$, which allows us to obtain the magnetic field near the ground:

$$B(z, t) = \frac{\rho_0}{\epsilon_0 H} (2z - (z_1 + z_2)t) \quad (12)$$

Unlike the electrostatic field, which depends only on the altitude z at which the static charges are located, the magnetic field depends not only on altitude z , but also on the time it takes for the charges to discharge to the ground. The range of variation of this temporal variable depends on the type of discharges caused by the charges in the cloud. The maximum magnetic field corresponds to a set of charges concentrated at altitude $z_{moy} = \frac{Z_1 + Z_2}{2}$, and is given by:

$$B(z_{moy}, t) = \frac{\rho_0}{\epsilon_0 H} (z_3 - z_1)t \quad (13)$$

However, for electrical charges assumed to be concentrated at the base of the observed cumulonimbus cloud, the corresponding magnetic field is

$$B(z, t) = \frac{\rho_0}{\epsilon_0 H} (z_2 - z_1)t \quad (14)$$

During the upward movement of warm air from the ground and the evaporation of water from seas and oceans, an interaction occurs between the warm air and the molecules surrounding the cloud. This is the ionization mechanism that promotes the movement of charges from the cloud to the ground. The magnetic induction created by the movement of charges gives rise to an induced current, the intensity of which depends on the type of discharges and the mobility of the ionized medium. The density vector of this induced current, also known as the diffusion current, is linked to the electrostatic and magnetic fields by Maxwell-Ampere's equation [18]:

$$\text{rot } \mathbf{B} - \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} = \mu_0 \mathbf{j} \quad (15)$$

Maxwell's law implies that if the electric field \mathbf{E} varies over time, in general, the magnetic field \mathbf{B} cannot be zero. In other words, a disturbance in one of the fields can cause a disturbance in the other, giving rise to electromagnetic waves. Taking into account equations (9) and (12), equation (15) allows us to determine

the expression of the norm of the current density vector induced by the moving charges in the conductive medium.

$$\|j\| = j = \sqrt{\left(\frac{2\rho_m}{\epsilon_0\mu_0 H} t\right)^2 + \left[\frac{\rho_m}{\mu_0 H}(2z - (z_2 + z_1))v\right]^2} \tag{16}$$

The term $v = \frac{dZ}{dt}$ in the second member of equation (16) accounts for the instantaneous velocity with which ionized charges at an altitude dz marked in the cumulonimbus cloud reach the ground at time dt . In addition to depending on these parameters, the velocity v at which the charges reach the ground depends on the type of discharge and the level of ionization of the surrounding environment. When the intensity of the current density induced by magnetic effects reaches extreme values, it has adverse effects on surrounding electrical equipment, requiring the use of protection systems to ensure their proper functioning.

3. Results and Discussion

By using the aerological diagram in **Figure 1**, which locates the coordinates of the cumulonimbus cloud in the vertical ascending Z -axis reference frame, we can deduce the maximum altitude of the cloud or summit $Z_3 = 15,300$ m, its base $Z_2 = 1300$ m, and the altitude of the city of Ndjama $Z_1 = 295$ m. To simulate the expressions of the field $E(z)$ and the corresponding potential $V(z)$, we worked under the assumption of [17], for which $\rho_m = \rho_{sol} = \rho_0 = \frac{1.0 \times 10^{-9} \text{ C}}{m^3}$. Assuming that the charge density of the cloud is more concentrated around the average altitude $(Z_2 + Z_3)/2$, the curve in **Figure 2** shows the variation in the electrostatic field around this average altitude. In contrast, **Figure 3** shows the variation in the electrostatic field assuming that the electric charge density is localized at the top of

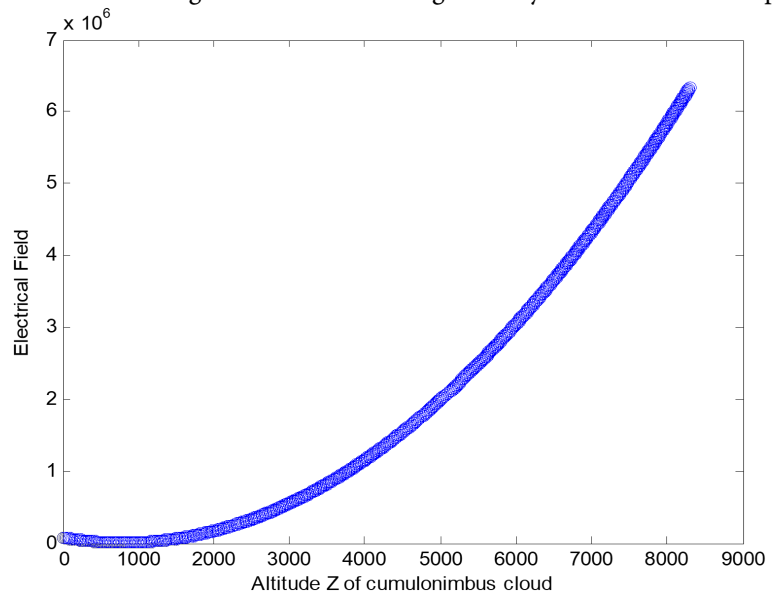


Figure 2. Variation in average electrostatic field intensity with altitude of cumulonimbus clouds.

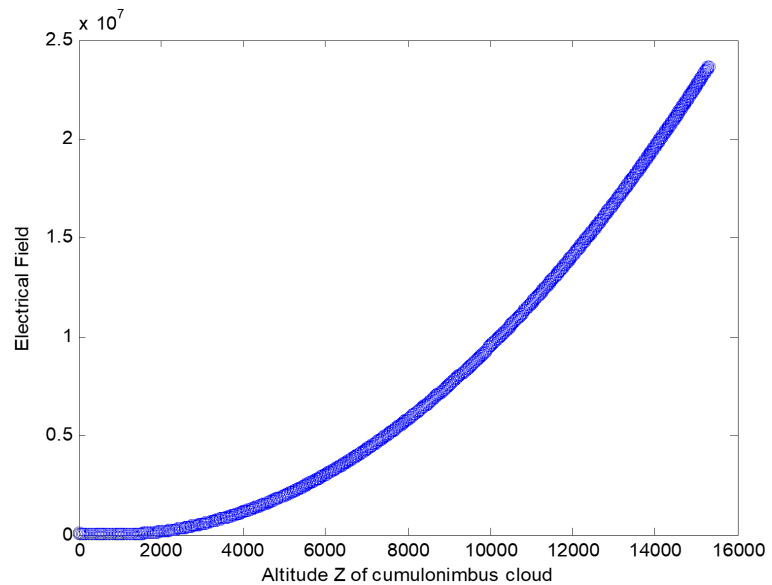


Figure 3. Variation in electrostatic field intensity with maximum altitude of cumulonimbus clouds.

the cloud. As can be seen in these two figures, the electrostatic field that would result from the discharge of the observed cloud reaches a value significantly higher than the disruptive field equal to 106 V/m, capable of ionizing all the surrounding air molecules in such a way as to promote the formation of a conductive medium conducive to the movement of electrical charges, which could potentially generate a lightning strike [15]. This very high-intensity electric field could cause leakage currents on certain surrounding power distribution lines [13], which would require the use of metal oxide surge arresters such as the zinc oxide surge arrester used to dissipate the harmful effects of lightning currents studied in the work of Zhou *et al.* (2018) [14]. This electric field, which is significantly stronger than the disruptive field, would lead to power surges that would impact distribution networks such as the National Electricity Company (SNE). Protecting these networks from the harmful effects of power surges would require the use or installation of extinguisher surge arresters such as those studied in the work of Safaei *et al.*, (2021) [7], those of J. Cao *et al.*, (2024) [8], and those of Paulino *et al.*, (2022) [12], in order to counteract the adverse effects on infrastructure and surrounding electrical distribution networks. For reassuring protection of the distribution networks of the national electricity company and those of Hassan Djamous International Airport in N'Djamena, located near where this cumulonimbus cloud is observed, it would be essential for the Chadian government to install a lightning arrester such as that described by Zhong *et al.* [13], which performs well in interrupting leakage current in the network. Another approach to protect against this would be to use a dynamic variable lightning arrester such as that described by Khoduz *et al.* [14], which can quickly mitigate leakage current caused by imperfections in various components of the distribution line, using a metal oxide-based current extinguisher, such as the lightning arrester developed by Zhou *et al.* [15],

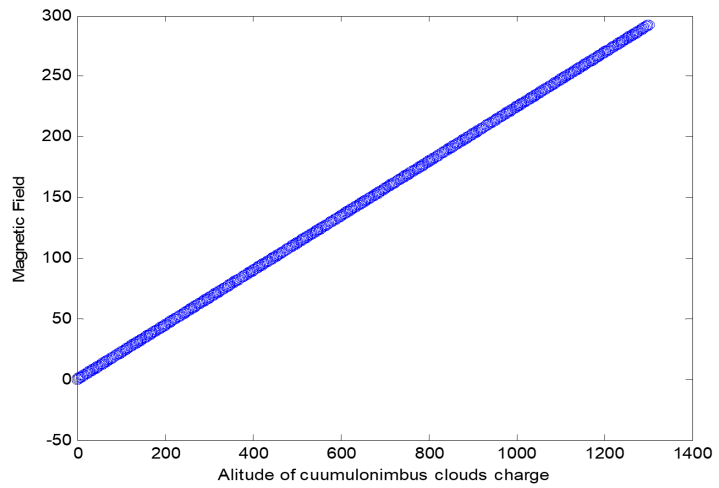


Figure 4. Variation in magnetic field intensity with altitude of charges assumed to be concentrated at the base of the cumulonimbus cloud.

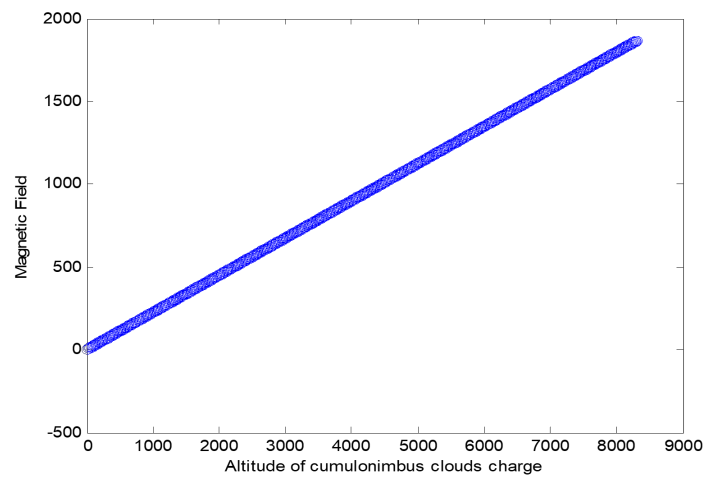


Figure 5. Variation in magnetic field intensity with the average altitude of cumulonimbus cloud loads.

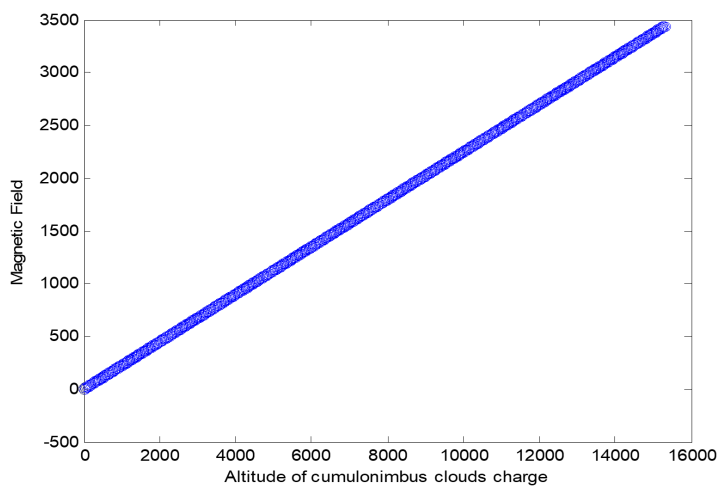


Figure 6. Variation in magnetic field intensity with altitude of charges assumed to be concentrated at the top of the cumulonimbus cloud.

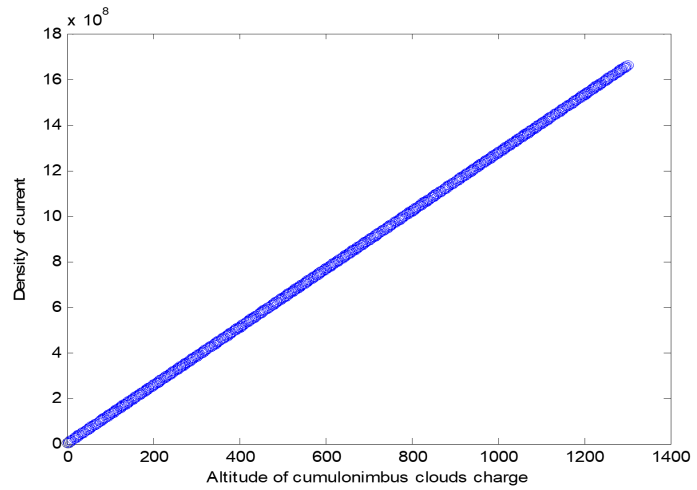


Figure 7. Variation in discharge current density with minimum altitude of cumulonimbus cloud charges.

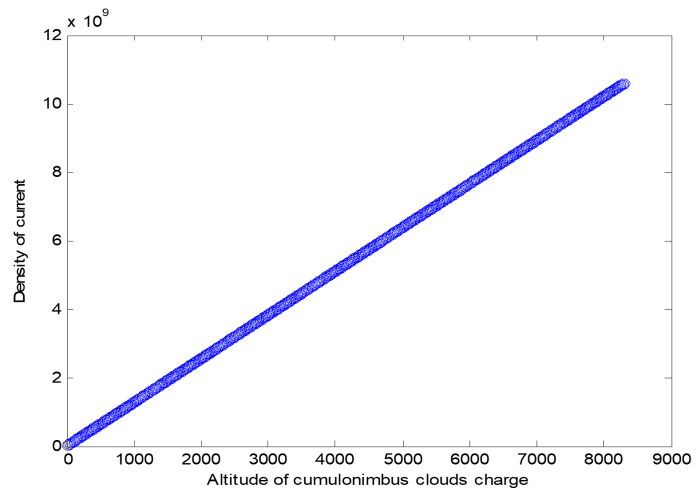


Figure 8. Variation in discharge current density with the average altitude of cumulonimbus cloud charges.

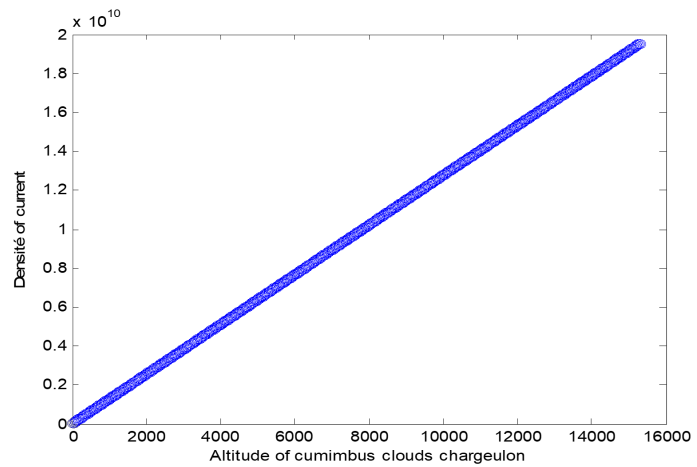


Figure 9. Variation in discharge current density with the maximal altitude of cumulonimbus cloud charges.

which uses zinc oxide to extinguish leakage current in the network.

In the northern part of Chad, which has a tropical climate, thunderstorms occur in some areas, with lightning strikes sometimes causing deaths among humans and livestock in certain villages. In the absence of popular scientific studies on the effects of lightning, and with no information on the possible presence of cumulonimbus clouds in the weather reports issued by the National Meteorological Agency (ANAM), these disasters caused by lightning strikes are most often interpreted as punishment from the gods. This was also the case in ancient Egypt, where mythology considered lightning to be the god of violence because of its harmful consequences on humanity and its activities.

According to Biot and Savart's law, the movement of a particle in a given space creates a magnetic induction field. **Figures 4-6** simulate the various variations in the magnetic induction field created by the movement of cloud charges assumed to be concentrated at the base, at mid-altitude, and at the top of the cloud, respectively. It should be noted that, for ionized charges at the base of the cloud (**Figure 3**), *i.e.*, for weak interaction between the updraft and the cumulonimbus cloud [20] [21], the intensity of the magnetic field remains well below 300 Tesla, it approaches 2000 Tesla for electrical discharges caused by charges located at the base Z_2 of the cloud (**Figure 4**). Finally, for strong interaction between the updraft and the cloud [22], in addition to the charges at the base of the cloud, those at the top Z_3 of the cloud are also ionized and drawn into the discharge. For a strong interaction between the ionizing air current and the cloud, the intensity of the magnetic field increases to reach a value of 3500 Tesla, as illustrated in (**Figure 5**). These observations are consistent with experimental findings, given that ionization is caused by the interaction of warm rising air currents with cloud charges. When these air currents interact only with charges located at the base of the cloud, other charges located above this base are not affected by this interaction. On the other hand, when the rising warm air current interacts with the charges located at the average altitude $(Z_2 + Z_3)/2$ and at the top Z_3 of the cumulonimbus cloud, those at the base of the cloud will inevitably be ionized in advance and carried along in the movement of the discharges, which explains the various variations observed in the three curves above. This electromagnetic field produced by this high-voltage electrical discharge would, in the absence of an effective protective device, cause heat stroke on existing electricity distribution networks, in particular on the distribution lines of the National Electricity Company, as reported in the work of Gill *et al.* [23]. As reported in this reference, this magnetic induction induced by the movement of charges in the cloud could interact with marine organisms such as fish in the Logone and Chari rivers near the area where this cloud was observed.

Under the effect of ionization by the upward air current, the environment in which the ionized charges move becomes conductive. Being in the magnetic induction field, any length z of the cloud discharging into the environment induces an electric current of density given by equation (16). **Figure 7** shows the variation in discharge current density for weak interaction between the updraft and the cumulonimbus cloud, *i.e.*, the variation in discharge current density caused by the

movement of charges located only at the base of the cloud at altitude Z . In contrast, **Figure 8** and **Figure 9**, which show the variations in current density at medium and maximum altitudes, respectively, highlight the increase in discharge current density with cloud altitude. In all three cases, the density of the current induced by the cloud discharge reaches values outside the safety limit range. This result is similar to that of Aida *et al.* [16], who showed in this reference that during electrical discharges, the current from lightning strikes can reach thousands of amperes, affecting electrical equipment. The high current density of a lightning strike causes enormous electrical stress on the power lines, leading to induced surges and the risk of fire. This can lead to equipment failure, power outages, and cascading failures across the network. The effect varies depending on whether the lightning strike is direct or indirect, but both can cause serious disturbances. Direct lightning strikes cause high-voltage pulses [24], and the electromagnetic fields simulated in this manuscript have very high intensities compared to the electromagnetic fields produced by indirect lightning strikes in the works referenced in [25] [26]. Apart from the curves in **Figures 2-3** showing the variation in the electric field, those describing the variations in the magnetic field and current density are simulated by setting the time variable equal to 10^{-3} s, which is the time it would take for a flame arrester to drain the discharge current to the ground, thereby rendering the surrounding power distribution networks harmless [16]. These very intense electromagnetic fields could cause power surges in the distribution lines of the National Electricity Company and the electrical equipment at Ndjamena's Hasan Djamous International Airport. This could lead to insulation breakdown, power outages, and damage to sensitive electronic equipment, even in the absence of a direct lightning strike [24]. The severity of these effects is influenced by factors such as the position of the lightning strike and the grounding and lightning protection configurations of the network. This electrical discharge could not only have a negative impact on the distribution lines of existing electrical networks, but could also cause serious loss of life, as reported in the work of Kalair *et al.* [27], who estimate that out of 50 lightning strikes occurring on earth per second, 10% of people living in that area are struck annually, with 20 to 25% of those victims dying. In the Maxwell-Faraday and Maxwell-Ampere equations we have just used, the electric and magnetic field vectors on the one hand, the electric field vectors, magnetic field vectors, and current density vectors on the other hand, are linked together by first-order differential operators, which explains the linear variations in magnetic field intensity in **Figures 4-6**, and current density in **Figures 7-9**.

4. Conclusion

In this manuscript devoted to electromagnetic phenomena induced by the presence of cumulonimbus clouds observed in N'Djamena, the use of the local form of Gauss's theorem and Maxwell's laws of electromagnetism enabled us to find analytical expressions for the electric and magnetic fields and the current density induced by the movement of charges in the cloud. Numerical simulation of these physical quantities suggests very high intensities, capable of completely ionizing

the surrounding environment and generating lightning. Such a discharge would have major impacts on surrounding power distribution networks and even on human activities. Given that Chadian weather reports rarely, if ever, forecast the presence of cumulonimbus clouds, this work serves as a wake-up call to the Agency for Air Navigation Safety in Africa and Madagascar (ASECNA) and the National Meteorological Agency (ANAM) to take into account the need to monitor the presence of such clouds when recording storm phenomena observed throughout the national territory.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Mason, B.J. (1993) *The Physics of Clouds*. Clarendon Press, 67.
- [2] Muyazeki, R., Dobshi, Y. and Nishita, T. (2002) Simulation of Cumulo-Form Clouds Based on Computational Fluid Dynamics, Euro Graphics/I. Navaro Alvaro and ph.susallek, Short Presentations.
- [3] Brylev, G.B., Gashina, S.B., Evteev, B.F. and Kamaldina, I.I. (2005) Kharakteristiki electricicheski aktivnyh zon V sloistoobraznyh oblakah-Leningrad, Hdrometizdat. p. 158.
- [4] Kochin, A.V. (2014) Formation of a Electric Charge in a Melting Layer of a Nimbostratus Cloud. *XV International Conference on Atmospheric Electricity*, Norman, 15-20 June 2014.
https://www.nssl.noaa.gov/users/mansell/icae2014/preprints/Kochin_132.pdf
- [5] Falade, J.A. and Adesanya, S.O. (2015) Numerical Simulation of Electrical Field and Charge Structure within an Isolated Thunderstorm. *Advances in Physics Theory and Applications*, **44**, 107-116.
- [6] Sundarajoo, S. and Soomra, D.M. (2022) Under Voltage Load Shielding and Penetration of Renewable Energy Sources in Distribution Systems: A Review. *International Journal of Modeling and Simulation*, **43**, 1002-1020.
- [7] Safaei, F. and Niasati, M. (2024) A New Method for Surge Arrester Placement in High-Voltage Substations Considering Environmental Effects. *IET Science, Measurement & Technology*, **18**, 550-563. <https://doi.org/10.1049/smt2.12208>
- [8] Cao, J., Du, Y., Ding, Y., Qi, R., Li, B., Chen, M., *et al.* (2022) Comprehensive Assessment of Lightning Protection Schemes for 10 Kv Overhead Distribution Lines. *IEEE Transactions on Power Delivery*, **37**, 2326-2336.
<https://doi.org/10.1109/tpwrd.2021.3110248>
- [9] Piantini, A. (2018) Analysis of the Effectiveness of Shield Wires in Mitigating Lightning-Induced Voltages on Power Distribution Lines. *Electric Power Systems Research*, **159**, 9-16. <https://doi.org/10.1016/j.epsr.2017.08.022>
- [10] Chen, H., Du, Y., Yuan, M. and Liu, Q.H. (2018) Lightning-Induced Voltages on a Distribution Line with Surge Arresters Using a Hybrid FDTD-SPICE Method. *IEEE Transactions on Power Delivery*, **33**, 2354-2363.
<https://doi.org/10.1109/tpwrd.2017.2788046>
- [11] Khodsuz, M. (2023) Externally Gapped Line Arresters Placement Effect on Transmission Line Lightning Performance Including the Frequency Response of the Ground-

- ing System. *IET Generation, Transmission & Distribution*, **17**, 4975-4990. <https://doi.org/10.1049/gtd2.13009>
- [12] Paulino, J.O.S., Barbosa, C.F., Lopes, I.J.S., Boaventura, W.C., Cardoso, E.N. and Guimarães, M.F. (2022) Lightning Protection of Overhead Distribution Lines Installed on High Resistivity Soil. *Electric Power Systems Research*, **209**, Article ID: 107952. <https://doi.org/10.1016/j.epsr.2022.107952>
- [13] Zhang, X., Dong, L., Zeng, G., Huang, S., Wu, L., Xiong, R., *et al.* (2018) Optimal Location of Surge Arresters on an Overhead Distribution Network by Using Binary Particle Swarm Optimization. 2018 *Chinese Automation Congress (CAC)*, Xi'an, 30 November-2 December 2018, 1841-1846. <https://doi.org/10.1109/cac.2018.8623397>
- [14] Khodsuz, M., Teymourian, M.H. and Seyyedbarzegar, S. (2024) New Criteria for Metal Oxide Surge Arrester Condition Monitoring Based on Leakage Current Analysis: Considering Non-Uniform Pollution Effect. *IET Generation, Transmission & Distribution*, **18**, 1072-1089. <https://doi.org/10.1049/gtd2.13123>
- [15] Zhou, S., Wang, H., Tian, H., Wu, Z., Cheng, J., Liu, P., *et al.* (2018) Transient Electric Field Calculation of Zinc Oxide Arrester under Lightning Impulse Voltage. 2018 *IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, Cancun, 21-24 October 2018, 231-234. <https://doi.org/10.1109/ceidp.2018.8544771>
- [16] Aida, G., Khodsuz, M. and Mashayekhi, V. (2025) The Lightning Protection Assessment of Distribution Lines with Considering Frequency Grounding System. *Iranian Journal of Electrical and Electronic Engineering*, **1**, Article No. 3437.
- [17] Picca, S.R. (2022) Laboratoire de Physique de l'Atmosphère, Université Paul Sabatier de Toulouse. Bulletin de l'union des physiciens, 866. <https://journalcra.com/sites/default/files/issue-pdf/49352.pdf>
- [18] Aliferis, A. (2012-2013) Cours d'électromagnétisme, Parcours des Ecoles d'Ingénieurs Plytech, 2eme année. <http://www.Polytech.unice.fr/aliferis>
- [19] Rainte, J. and Petit, J.-P. (1995) Transferts thermiques, cours et données de base. Dunod.
- [20] Aspelmeyer, M., Kippenberg, T.J. and Marquardt, F. (2014) Cavity Optomechanics. *Revue of Moderne Physics*, **86**, 1391-1452.
- [21] Shahidani, S., Naderi, M.H., Soltanolkotabi, M. and Barzanjeh, S. (2014) Steady-State Entanglement, Cooling, and Tristability in a Nonlinear Optomechanical Cavity. *Journal of the Optical Society of America B*, **31**, Article No. 1087. <https://doi.org/10.1364/josab.31.001087>
- [22] Foulla, D.P., Djourwé, P., Kingni, S.T. and Engo, S.G.N. (2017) Optomechanical Systems Close to the Conservative Limit. *Physical Review A*, **95**, Article ID: 013831. <https://doi.org/10.1103/physreva.95.013831>
- [23] Gill, A.B., Huang, Y., Spencer, J. and Gloyne-Philips, I. (2012) Electromagnetic Field Emitted by High Voltage Alternating Current Offshore Wind Power Cables and Interactions with Marine Organisms. *Electromagnetic in Current and Emerging Energy Power Systems Seminar*, London.
- [24] Belko, D.O. and Podporokin, G.V. (2016). Analysis of Current Distribution among Long-Flashover Arresters for 10 Kv Overhead Line Protection against Direct Lightning Strikes. 2016 *33rd International Conference on Lightning Protection (ICLP)*, Estoril, 25-30 September 2016, 1-6. <https://doi.org/10.1109/iclp.2016.7791511>
- [25] Punekar, G. and Kandasamy, C. (2011) Indirect Effects of Lightning Discharges. *Serbian Journal of Electrical Engineering*, **8**, 245-262. <https://doi.org/10.2298/sjee1103245p>

- [26] Adi Kusuma, A., Aditya Pramana, P.A., S.D.A. Harsono, B.B. and Sofiaro Munir, B. (2018) Effect of Indirect Lightning Strike to 66 Kv Transmission Line in Java-Bali System. *MATEC Web of Conferences*, **197**, Article No. 11001.
<https://doi.org/10.1051/mateconf/201819711001>
- [27] Kalair, A., Abas, N. and Khan, N. (2013) Lightning Interactions with Humans and Lifelines. *Journal of Lightning Research*, **5**, 11-28.
<https://doi.org/10.2174/1652803420131029001>