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RESEARCH ARTICLE

ANALYTICAL AND NUMERICAL STUDY OF ELECTRICAL DISCHARGES CAUSED BY THE PRESENCE OF CUMULONIMBUS CLOUDS OBSERVED IN THE CHADIAN ATMOSPHERE

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ABSTRACT

The study of electrical phenomena in the atmosphere is very interesting because it allows us to predict the dangers caused by lightning currents, which result from an electrical discharge from an existing cumulonimbus cloud. Simulation of the electrostatic properties of a possible discharge from the cumulonimbus cloud, observed in N'Djamena, shows that lightning can occur with an electric field able to ionize molecules in the surrounding environment, and a very intense electrostatic potential, similar to high-voltage electrical discharges.

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INTRODUCTION

The Earth's atmosphere is a gaseous envelope in which we live. It is the site of numerous phenomena such as the electrical discharges observed during thunderstorms (1). It is subdivided into several layers, including the high atmosphere, which is subject to X-rays and many other ionizing radiations, as well as the molecules and atoms found there under their influence. The high atmosphere is subject to solar radiation, which is one of the factors that ionizes atoms and molecules, while in the lower atmosphere, specifically in the troposphere, meteorological phenomena occur considerably. It is characterized by ultraviolet radiation, natural radioactivity from the ground, and cosmic radiation emitted by the Earth. The troposphere is characterized by a strong vertical variation in temperature (2), due to the fact that most of the heat transfers it receives come from the Earth's surface, which transmits it through heat exchange when water changes state (3). Water receives binding energy when it evaporates from the Earth's surface. This process leads to the formation of cumulonimbus clouds, allowing the appearance of electrical charges, with the high level containing positive charges and the lower level containing negative charges, the discharge of which can potentially cause lightning. Lightning can be defined as a natural phenomenon of electrical discharges that can occur when a large amount of static charge accumulates in areas of storm clouds. It is a common phenomenon that behaves like a perfect generator of electrical current. In the context of climate change, extreme weather events (2) such as thunderstorms accompanied by lightning are becoming increasingly frequent, causing enormous damage to infrastructure. These electrical discharge phenomena, resulting from the presence of cumulonimbus clouds in a given region (4;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 electrical discharge phenomenon 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 $E(d)=10^6 v.m^{-1}$ (disruptive field) in humid air. This disruptive field is responsible for the ionization of surrounding air molecules and the formation of a conductive medium conducive to the movement of electrical charges that can potentially cause lightning. Depending on the intensity of the electric field accompanying these discharge phenomena, electrical discharges could potentially be observed, which could generate lightning, having adverse consequences on all human activities (6). As a result, a vast amount of scientific research has been devoted to this fascinating field, modeling lightning as an electromagnetic wave with a view to protecting electrical installations from the effects of lightning and analyzing the effects of lightning surge currents (7; 8). In references (9; 10), the authors analyzed the effects of lightning and its coupling to the electrical grid. It appears that despite the efforts of researchers, the complexity of lightning and its accompanying effects remain fertile ground for further study in order to ensure the reliable protection of 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 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 concern in Paulino publication (12). It appears 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. Given that the cumulonimbus clouds causing these discharges are characterized by physical parameters that are dynamic in time and space, the work in reference (13) show that the design of a dynamic variable surge arrester equipped with a metal oxide switch significantly reduces 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 surges caused by these discharges. By using zinc oxide as the switch, the surge arrester used in the work (14) 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.

In Chad, from a meteorological point of view, little attention is paid to studies of electrical discharge phenomena in the atmosphere. Apart from a few phenomena observed in Chad, weather forecasts rarely mention electrical discharges or the presence of cumulonimbus clouds responsible for electrical discharges. The effects of lightning are sometimes mentioned in weather reports. In light of the above-mentioned studies reporting the harmful effects of lightning caused by the presence of cumulonimbus clouds, we are concerned about whether the electric field characterizing the cumulonimbus cloud observed on July 16, 2021, in Chad, is 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 present the materials and methods used to study the phenomenon. In the third section, we will discuss our results and compare them with those found in the literature on the subject. Finally, the conclusion will follow.

MATERIALS AND METHODOS

Materials

In terms of equipment, we used MATLAB software to plot the curves of energy stored in the different atmospheric layers.

Data, source, and processing: For our numerical simulation, we used the value of the ionized charge in the atmosphere, which averages 550,000 C according to (15). The different thicknesses of the atmospheric layers (troposphere, stratosphere, mesosphere, thermosphere) are assimilated to their radii due to the spherical structure of the atmosphere. To simulate the electric field, we used the aerological diagram for July 16, 2021, obtained at Hassan Djamous International Airport in N'Djamena (source: ASECNA), see Figure 1.

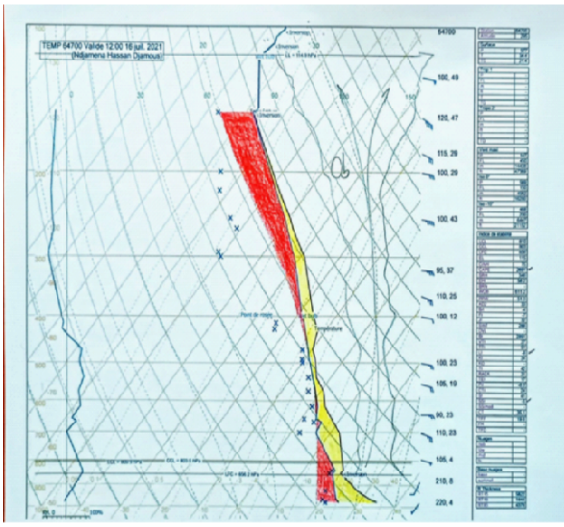

Figure 1: Aerological diagram observed on July 16, 2021, at Hassan Djamous International Airport in N'Djamena (source: ASECNA). In this diagram, the intersection of the air temperature variation curves and the dew point variation curves gives the top of the cumulus nimbus cloud at altitude Z_3. The base of 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 gives the altitude Z_1 of the city of N'Djamena.

METHODOLOGY

Our methodological approach consists of using Poisson's equation, the solution of which will give the expression of the potential, and the local form of Gauss's theorem to determine the electric field characterizing the cumulonimbus cloud observed in Chad, which would make it possible to know whether this cloud would result in a simple electrical discharge or a case of lightning.

We use Poisson's equation

$$\Delta V + \frac{\rho}{\varepsilon_0} = 0 \quad \text{(Eq.1)}$$

Due to the spherical structure of the atmosphere, and taking into account the fact that the potential is radial, the Laplacian is written as:

$$\Delta = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial}{\partial r}\right) \quad \textbf{(Eq.2)}$$

Solving Laplace's equation leads to the potential in the troposphere expressed as:

$$V(r) = \frac{KQ}{2R_T^2}\left(3 - \frac{r^2}{R_T^2}\right) \quad \text{(Eq.3)}$$

The potential in the other high layers of the atmosphere is given by the expression:

$$V(r) = \frac{KQ}{r} \quad \text{(Eq.4)}$$

The energy stored in this high part of the atmosphere is:

$$W(r) = \frac{KQ^2}{r} \quad \text{(Eq.5)}$$

That stored in the troposphere is:

$$W(r) = \frac{KQ^2}{2R_T^2}\left(3 - \frac{r^2}{R_T^2}\right) \quad \text{(Eq.6)}$$

To determine the electric field characterizing the cumulonimbus cloud represented by the aerological diagram in Figure 1, the volume density of loads ρ(z) is a function that varies linearly with altitude according to the relationship:

$$\rho(z) = Az + B \quad \text{(Eq.7)}$$

Where A and B are two constants to be determined. On the diagram of Figure 1, 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.

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

$$\begin{cases} -\rho_0 = B + AZ_1 \\ \rho_0 = B + AZ_2 \end{cases} \quad \text{(Eq.8)}$$

whose solution gives the expressions of the constants

$$A = \frac{2\rho_0}{Z_2 - Z_1} \quad \text{(Eq. 9)}, \qquad et \;\; B = -\frac{A}{2}(Z_1 + Z_2) \quad \text{(Eq.9)}$$

The charge density ρ(z) in the cumulonimbus cloud will be given by:

$$\rho(z) = \frac{2\rho_0}{H}\left(Z - (Z_1 + Z_2)\right) \quad \text{(Eq.10)}$$

With $H = Z_2 - Z_1$. Integration in space of the local form of Gauss's theorem

$$div\overrightarrow{E(z)} = \frac{\rho(z)}{\epsilon_0} \quad \text{(Eq.11)}$$

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

$$E(z) = \frac{\rho_0}{\epsilon_0 H}(Z^2 - (Z_1 + Z_2)Z) + C \quad \text{(Eq.13)}$$

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

$$C = \frac{1}{\varepsilon_0}\left(\rho_{sol} Z_1 + \frac{\rho_m Z_1 Z_2}{H}\right) \quad \text{(Eq.14)}$$

$$E(z) = \frac{\rho_0}{\epsilon_0 H}(Z^2 - (Z_1 + Z_2)Z) + \frac{1}{\varepsilon_0}\left(\rho_{sol} Z_1 + \frac{\rho_m Z_1 Z_2}{H}\right) \quad \text{(Eq.15)}$$

Knowing that the electric field derives from the electric potential, integrating the electric field above gives the expression for the potential

$$V(z) = \frac{\rho_0}{\varepsilon_0 H}\left(\frac{1}{3}Z^3 - \frac{1}{2}(Z_1 + Z_2)Z^2\right) + \frac{1}{\varepsilon_0}\left(\rho_{sol} Z_1 + \frac{\rho_m Z_1 Z_2}{H}\right)Z + \beta \quad \text{(Eq.16)}$$

Using the continuity of the potential at altitudes Z_1 and Z_2 as was done for the electrostatic field, we obtain the expression for the constant

$$\beta = \frac{\rho_{sol} Z_1}{\varepsilon_0}\left(\frac{Z_1}{2} - Z_2\right) - \frac{\rho_m}{2\varepsilon_0 H}\left(\frac{Z_2}{3} + Z_1\right) \quad \text{(Eq.17)}$$

RESULTS AND INTERPRETATIONS

For our numerical simulations, we used the value of the ionized charge in the atmosphere, whose average value is around 550,000 C (15). The different thicknesses of the atmospheric layers (troposphere, stratosphere, mesosphere, and thermosphere) are comparable to their respective radii due to the spherical structure of the atmosphere. The macroscopic constant $K = 9.10^9$ SI.

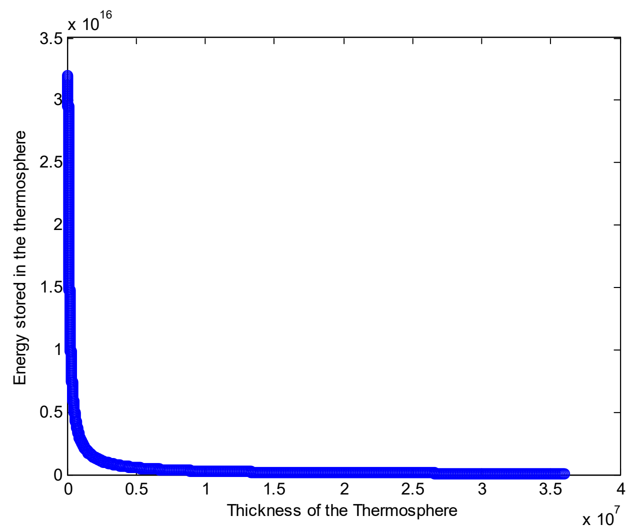

Figure 2. Variation in electrostatic energy stored in the thermosphere with layer thickness

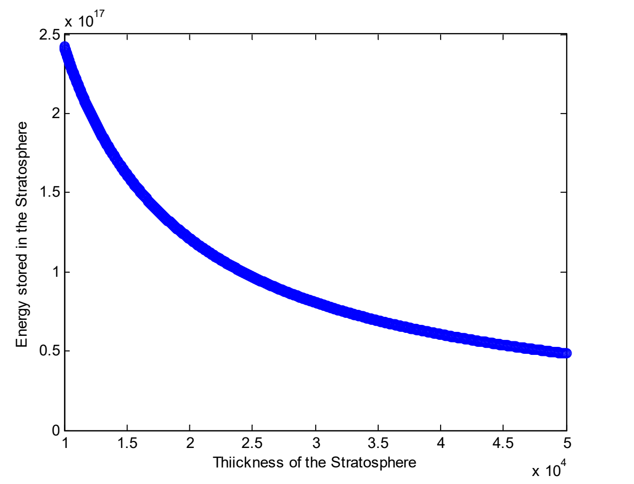

Figure 3. Variation in electrostatic energy stored in the stratosphere with layer thickness

The variation in energy stored in the three layers of the atmosphere shows that this energy decreases with the radius of the layer. From the thermosphere to the stratosphere (Figures 2 and 3), electrostatic energy, represented by upward-curving lines, increases considerably. The particles found there are in a quasi-stable state that is less sensitive to thermal agitation. At the level of the troposphere (Figure 4), the lowest layer of the atmosphere, the stored electrostatic energy is at its maximum for low values of the layer radius, i.e., close to the Earth. The downward concavity of the variation curve for this energy shows that the various particles found there, such as aerosols, are in a state of instability due to the thermal agitation resulting from collisions between these molecules. This increase in temperature due to thermal agitation creates conditions conducive to the formation of warm air at low altitudes. The rise of warm air at high altitudes will interact with the cold air. During this rise, water droplets that evaporate from the surface of the seas and oceans will condense into ice crystals when they encounter the cold air at high altitudes. This is the

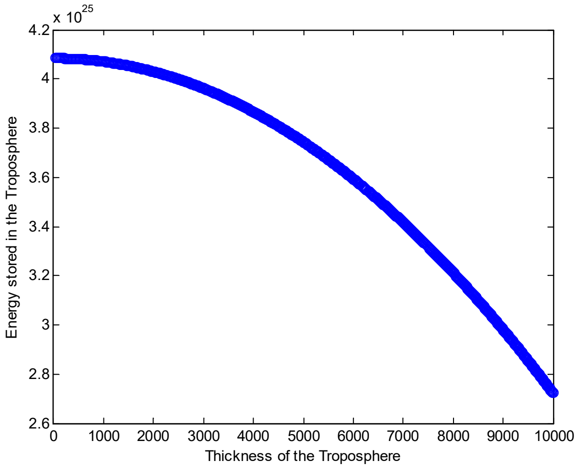

Figure 4. Variation in electrostatic energy stored in the troposphere with layer thickness

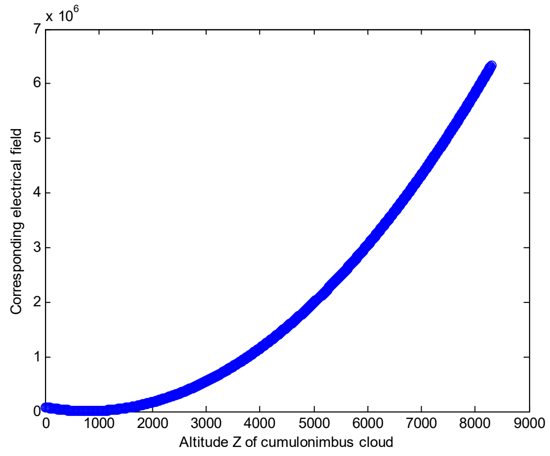

Figure 5. Variation in average electrostatic field intensity with altitude of cumulonimbus

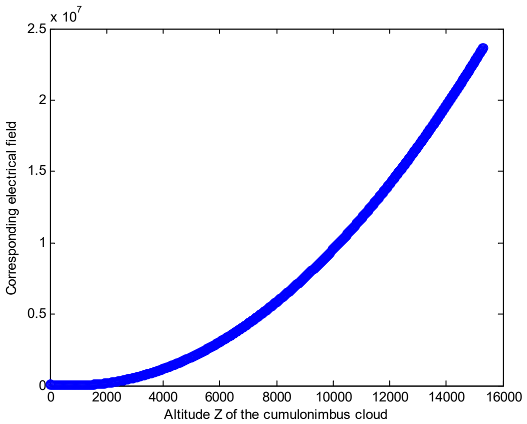

Figure 6. Variation in electrostatic field intensity with maximum altitude of cumulonimbus cloud

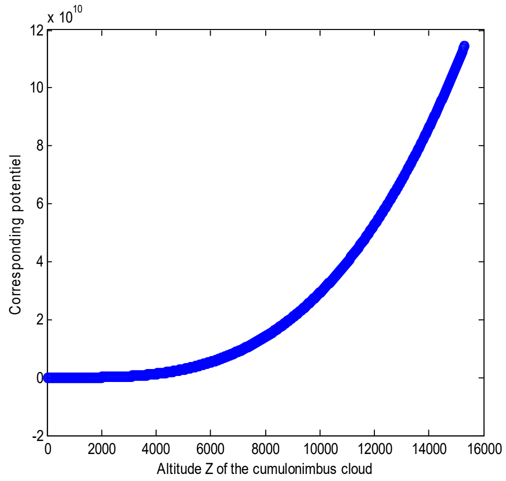

Figure 7. Variation in electrostatic potential with altitude for electric charges concentrated at the top Z_3 of the cumulonimbus cloud

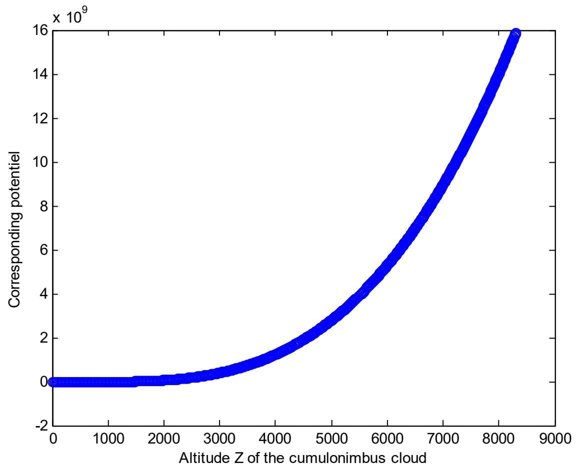

Figure 8. Variation in electrostatic potential with altitude for electric charges concentrated at the average altitude (Z2+Z3)/2 of the cumulonimbus cloud.

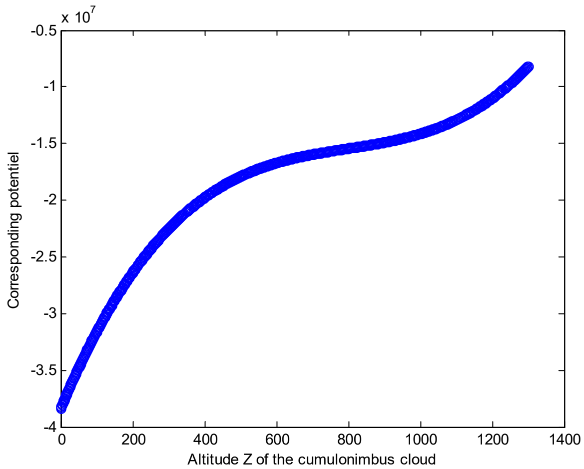

Figure 9. Variation in electrostatic potential with altitude for electric charges concentrated at the base Z2 of the cumulonimbus cloud

mechanism behind the formation of cumulonimbus clouds, which can cause lightning. This instability observed in the troposphere is proof that electrical, meteorological, and optical phenomena such as lightning (6), rainbows, halos (2; 16), inferior mirages (17; 18; 19), and superior mirages (20) can only be observed in the troposphere. 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=15300m, its base Z_2=1300 m, and the altitude of the city of N'Djamena 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 reference (21) for which $\rho_m = \rho_{sol} = \rho_0 = \frac{1.0.10^{-9}C}{m^3}$. Assuming that the charge density of the cloud is more concentrated around the average altitude $(Z_2+Z_3)/2$, the curve in Figure 5 shows the variation of the electrostatic field around this average altitude. However, Figure 6 shows the variation in the electrostatic field assuming that the density of the electric charges is localized at the top of 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 10^6 V/m, able to ionize all the surrounding air molecules in such a way as to promote the formation of a conductive medium conducive to the movement of electric 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).

During electrical discharges, the electrostatic potential produced on the ground by the charges in the cloud often reaches very high values, requiring the use of lightning arresters to protect existing electrical networks from damage. Figures 7, 8, and 9 show the variation in electrostatic potential produced on the ground by the electrical charges in the cloud, assumed to be concentrated at the top, between the base and the top, and finally at the base of the observed cumulonimbus cloud. These three figures show that during cloud discharge, there is a variation in high-voltage potential, which can damage electrical distribution networks such as the National Electricity Society (SNE). Protecting these networks from the harmful effects of overvoltage 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 consequences on infrastructure and surrounding electrical distribution networks.

These variation curves show that the potential generated by the cloud discharge increases with the altitude Z of the cloud. This is perfectly normal, because the higher the electrical charges in the cloud are, the more they interact with the warm air, which can cause complete ionization of the cloud, promoting a high-voltage electrical discharge. In the southern 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.

CONCLUSION

In this paper devoted to the cumulonimbus cloud observed in N'Djamena, we used the local form of Gauss's theorem, an analytical and numerical study of the field and potential produced on the ground by a possible electrical discharge from the cloud. The numerical simulation of the electrostatic potential suggests an electrostatic field intensity greater than the disruptive electric field intensity capable of completely ionizing the surrounding environment and generating a lightning strike. Similarly, the simulation of electrostatic potential leads to variations in potential in the range of high-voltage electrical discharges, requiring the installation of lightning arresters. Given that Chadian weather reports rarely, if ever, predict 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.

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