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Lightning under Different Land Use and Cover, and the Influence of Topography in the Carajás Mineral Province, Eastern Amazon

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Abstract: Knowledge about regions where lightning occurs is important both for understanding storm development and direction. This can assist in very short-term weather forecasts and in developing lightning warning systems, aiming to minimize exposure of people and equipment in the open sky. A survey on the occurrence of lightning in different types of land use and coverage and different elevation strata in the region of the Itacaiúnas River watershed (IRW), located in the Carajás Mineral Province, in the Eastern Amazon, from 2012 to 2021 was conducted. The results showed significant differences in the occurrence of lightning in mining areas and deforested areas. When comparing the large proportion of deforested areas with the mining area, the results suggested that in IRW mining areas, the lightning incidence is expressively higher. The assessment of electrical activity at different elevations in the region suggested that the slope of the terrain and its thermodynamic effects on the formation of storms have more influence than altitude on lightning activity. The results showed the importance of adopting initiatives aimed at protecting both the local population and mining workers, as well as equipment exposed to the open sky in this region.

Keywords: lightning; land cover and land use; topographic effects; Itacaiúnas River watershed

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1. Introduction

Research into preferred regions of lightning activity (cloud-to-ground—CG and intracloud—IC) has become increasingly necessary due to the increased frequency of severe storms [1], widely reported by the Intergovernmental Panel on Climate Change (IPCC) in its latest reports [2].

The IPCC also warns about the influence of land use and cover changes (LULC) on the formation and intensification of storms. These factors are fundamental in land–atmosphere interactions, reflecting changes in climate on local, regional, and global scales [3]. In this context, several studies have investigated this relationship, and the conclusions vary depending on the geographic region and the type of soil and vegetation in question [4,5].

At the global level, changes in LULC affect precipitation, with significant signals most evident over degraded regions such as East Asia, West Africa, and South America [6]. Changes in LULC cause a reduction in net radiation and evapotranspiration, which generates changes in atmospheric circulation patterns and variations in the magnitude and pattern of moisture flux convergence and subsequent reduction in precipitation accumulations. On the other hand, these changes increase the surface air temperature during summer due to reduced evapotranspiration. In contrast, temperatures in the upper troposphere become even colder due to the smaller amount of latent heat that is released in the condensation of water vapor, which generates a weaker circulation in regions of change in LULC [6].

Land cover changes associated with urbanization create higher air temperatures compared to those in surrounding rural areas, known as the urban heat island effect. Studies indicate that the contributions of anthropogenic forcing associated with urbanization also affect the formation of convective storms [7,8]. Considering the central part of the Amazon, the largest tropical forest in the world, research has shown that in recent decades, the increase in lightning incidence has been proportional to the increase in urban area. Thus, replacing forests with urban areas tends to increase the frequency of lightning in this region [9].

Increases of 60 to 70% in lightning density in urban areas compared to their surroundings have also been observed in Taiwan [7]. The spatial distribution of CG lightning is similar to that of the heat islands in Taipei, which supports the thermal influence hypothesis. Nevertheless, in this region, the concentrations of particulate matter with a diameter of 10 µm (PM10) and sulfur dioxide (SO2) showed positive linearity with the number of CG lightning events, suggesting relationships with the influence of aerosols, as also discussed in other works [10,11]. These results indicate that both hypotheses (thermal and aerosol) must be considered to explain the increase in CG lightning in urban areas.

In addition to the influence of land cover and the interference of its different uses on lightning incidence, studies show that topography is also a factor that defines patterns of lightning activity in a region [12,13]. In Southern Brazil, it was observed that the highest incidence of lightning is not directly related to altitude per se but appears to have a linear relationship with sections of steeper terrain [12]. In this study, it was also observed that the diurnal variation in CG lightning is smaller at low altitudes than at high altitudes. This result was associated with the occurrence of mesoscale convective systems (MCSs) at low altitudes in the northwestern region of Southern Brazil.

Additionally, it has been observed in the United States that the intensification of deep convection in complex terrain can influence not only the CG lightning incidence and the location of the first flash of a storm but also the physical parameters of CG lightning [13].

Thus, this work presents a survey on lightning activity in the Itacaiúnas River watershed (IRW), located in the Carajás Mineral Province, in the Eastern Amazon. This is a region that is characterized by a steep relief, given the presence of the Serra dos Carajás with approximately 900 m of altitude.

The objective was to evaluate the lightning activity in different types of land use and coverage in the IRW, altitudes, and slopes to understand possible relationships between these elements and the development of storms in one of the areas with a high lightning incidence in Brazil. In addition, this basin contains the largest deposits of polymetallic minerals that are industrially extracted from iron, manganese, copper, and nickel ores, as well as the artisanal exploration of gold, precious stones, and others [14].

Finally, one of the primary justifications for the development of this study was that research assessing lightning activity in mining areas within the Amazon rainforest is in its early stages. However, it is greatly relevant for providing technical–scientific support in weather forecasts, as well as for developing warning systems aimed at protecting people and equipment exposed in open-pit mines.

2. Materials and Methods

2.1. Study Area

The analysis of the lightning incidence in different types of land cover and use was developed for the Itacaiúnas River watershed (IRW) region, which has an area of approximately 42,000 km^2 located in the Carajás Mineral Province in the east of the Amazon (Figure 1).

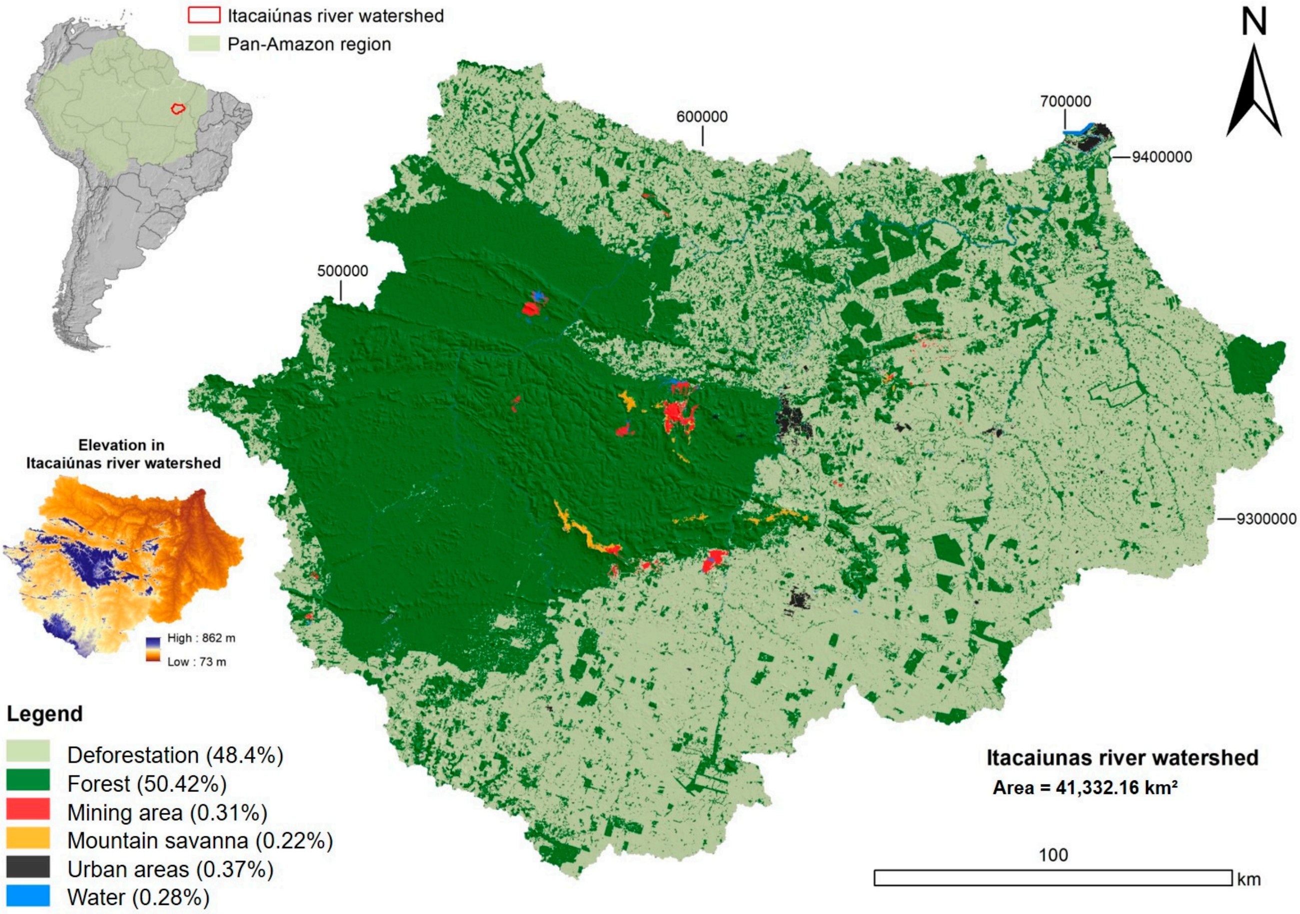


Figure 1. Location of the Itacaiúnas River watershed (IRW) and its respective land cover and land use types. The elevation map of the region is also displayed on the left.

The basin has 1/3 of its area protected (conservation units and indigenous lands), which is indicative of the environmental significance of the region for biodiversity conservation [15]. Deforested areas correspond to approximately half of the basin area and are predominantly used for pastures. Approximately 35% of the cattle herd in the state of Pará comes from BHRI [16], and the assets produced in the region, especially mineral resources, account for 25% of the GDP of the State of Pará [17].

2.2. Data

Lightning data used in this article were obtained by combining data from two lightning location networks (LLN), called BrasilDAT and RINDAT, with data from Geostationary Lightning Mapper (GLM) on board GOES-16 satellite.

BrasilDAT uses the Earth Networks technology, that detects and monitors cloud-to-ground and intracloud lightning and was implemented in 2011 by the Atmospheric Electricity Group (ELAT) of the National Institute for Space Research (INPE) [18]. BrasilDAT uses the time-of-arrival (TOA) method to detect intracloud pulses and cloud-to-ground strokes and operates in the frequency range between 1 Hz and 12 MHz. This method employs three or more sensors to determine the moment the electromagnetic radiation emitted by lightning reaches the sensor, and with the relative temporal difference in the time of arrival at the sensors, hyperbolic curves are defined for each pair of sensors that detect lightning. These hyperboles indicate the possible lightning locations according to the measured time differences, so the point of intersection indicates the possible lightning location.

RINDAT uses Vaisala technology (LS sensors). The system uses technologies called TOA and “Magnetic Direction Method” (MDF). In this method, lightning detection is performed using sensors capable of measuring the direction of a lightning strike, determined by the use of two magnetic loops orthogonal to each other. When two or more sensors detect a discharge, the intersection of the lines defined by their respective azimuths (angle relative to true north) defines the point of contact. The use of three or more sensors allows for determining the location at the point of contact of the return stroke discharge with the ground, through an optimization process of least squares of the locations obtained from each pair of sensors. The accuracy of lightning location information by RINDAT is, on average, 500 m within the perimeter defined by the position of the remote reception stations. The system operates through GPS, which provides lightning timing information with resolutions of up to 300 nanoseconds [19,20].

Finally, the GLM is a single-channel near-infrared optical transient detector carried aboard the GOES-16 satellite in geostationary orbit. This orbital position allows the GLM to make detections in dedicated areas over the Americas, typically including regions with sparse data such as mountainous areas and vast oceanic regions. Thus, the total lightning data from the GLM have significant potential for cloud-scale data assimilation applications to improve storm event predictions, especially when combined with other storm-scale datasets such as ground-based radar data [21,22].

The data from different sources are combined based on time and space criteria, such as events with same millisecond and less than 10 km of distance are considered as unique events. The detection efficiency of CG lightning for the studied region is around 80%, while for IC lightning, it is below 30% (Figure 2). Detailed information about this network can be found in [23].

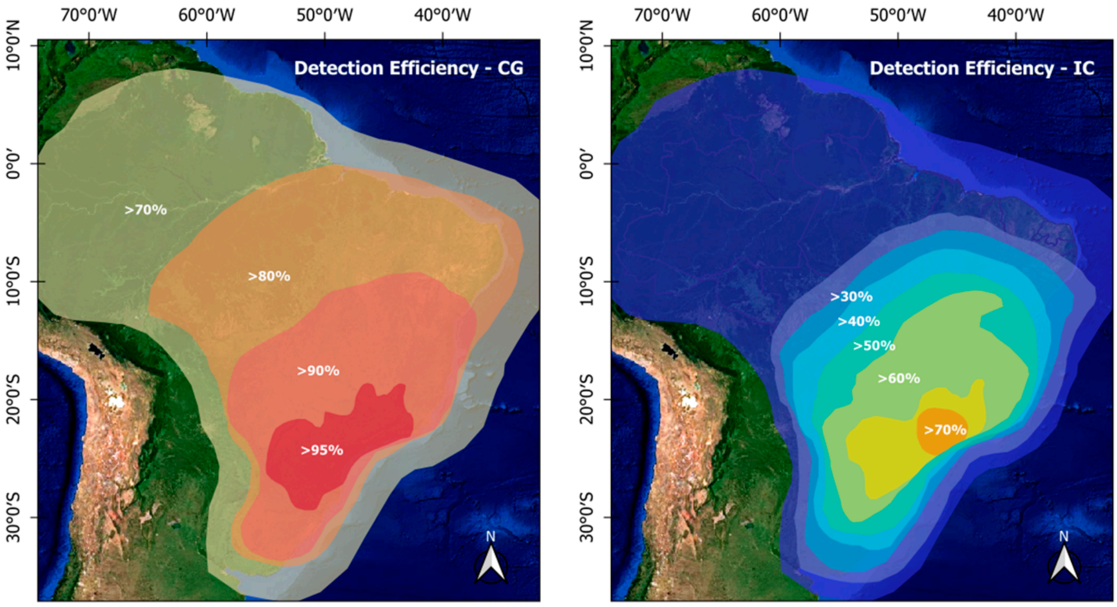


Figure 2. Maps of cloud-to-ground (CG) and intracloud (IC) lightning detection efficiency.

The land use and land cover data were derived from mappings conducted by [24], who utilized imagery from Landsat-8 and Sentinel-2A satellites. The land cover and land use classes, along with a detailed change detection approach, were developed through geographic object-based image analysis (GEOBIA—Geographic Object-Based Image Analysis).

Three land cover patterns were used: forest, mountain savanna, and water; and three land use patterns: deforestation (pasturelands), mining, and urbanization (Figure 3). In the land cover classes, forested areas encompassed ombrophilous forests with closed and open canopies exceeding 30 m in height. The open and shrubby deciduous mountain savanna covered regions at high altitudes, approximately 600 to 900 m. Bodies of water, on the other hand, were represented by rivers and small lakes.

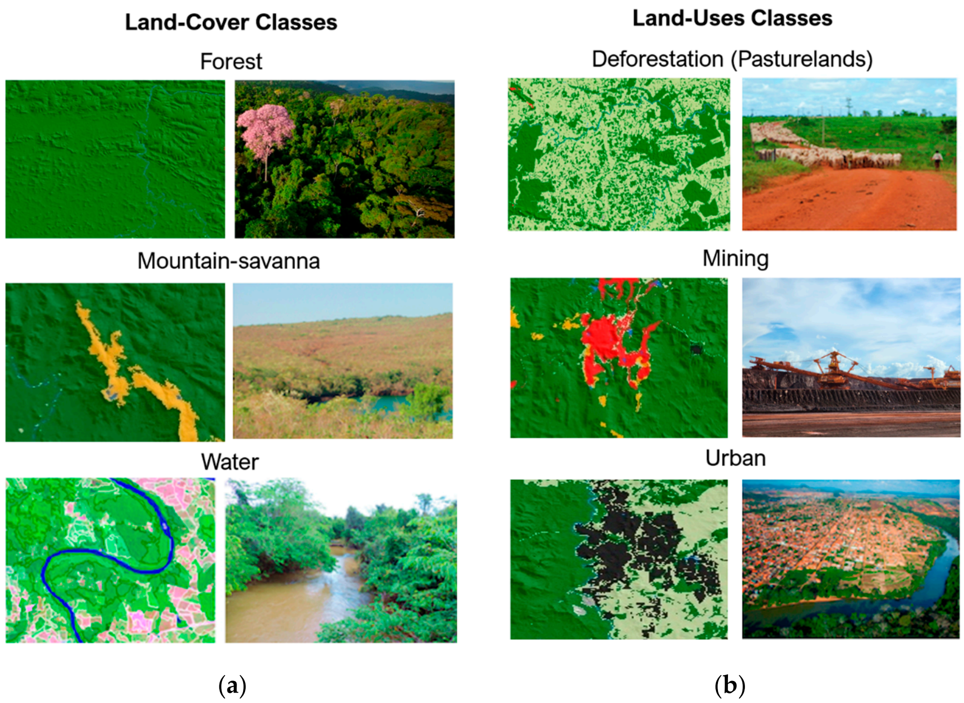


Figure 3. Classification of different land cover (**a**) and land use (**b**) types in the Itacaiúnas River watershed (IRW). Source: adapted from [24].

Elevation data were obtained from the Geomorphometric Database of Brazil—TOPODATA [25], provided free of charge by the National Institute for Space Research (INPE). TOPODATA is a project that offers a digital elevation model with local adjustments and a spatial resolution of 30 m, derived from the original Shuttle Radar Topography Mission (SRTM) data, covering the entire Brazilian territory.

2.3. Methodology

The lightning and land use/land cover data were assessed to extract potential relationships between land cover types and the frequency of lightning activity. Subsequently, possible associations between lightning incidence and topography, including altitude and slope, were also evaluated.

For the spatial analysis of lightning activity, the kernel density estimator (KDE) was applied, with the scale varying for each year to facilitate visualization across all years under investigation. Furthermore, over the years, lightning detection technology has seen improvements, and conducting the analysis with the same scale could potentially suggest an increase in the number of lightning events over time. While this increase may occur due to the intensification of storms [2], different scales were chosen as a precaution in the data evaluation. Moreover, the objective of this figure was to provide a qualitative rather than quantitative assessment of lightning activity in the study region.

KDE is a nonparametric method for estimating the probability density distribution of a dataset. In broad terms, KDE is one of the types of analyses derived from the estimation of point data intensity, which means estimating the number of events per unit area [26]. In this case, the higher the clustering of lightning activity points in a specific area within the IRW, the higher the intensity calculated by KDE.

Given $X_1, \ldots, X_n \in R^d$ as a random sample from a distribution F with density f, the kernel density estimation of f, also known as the Parzen window estimation, is a non-parametric estimation given by:

$$\hat{f}KDE(x) = \frac{1}{n}\sum_{i=1}^{n} k_\sigma(x, X_i)$$

where k_σ is a kernel function with bandwidth σ. To ensure that $\hat{f}KDE(x)$ is a density, we assume that the kernel function satisfies $k_\sigma(\cdot,\cdot) \geq 0$ *e* $\int k_\sigma(x,\cdot)dx = 1$. We also assume that $k_\sigma(x,x')$ is translation invariant, such that $k_\sigma(x - z,x' - z) = k_\sigma(x,x')$ for all x,x' e z.

Furthermore, we require that k_σ be positive semi-definite, which means that the matrix $(k_\sigma(xi,xj))1 \leq i,j \leq m$ is positive semi-definite for all positive integers m and all $x_1, \ldots, x_m \in R^d$. Well-known examples of kernels that satisfy all the properties above include the Gaussian kernel:

$$k_\sigma(x,x') = \left(\frac{1}{\sqrt{2\pi\sigma}}\right)^d exp\left(-\frac{\|x - x'\|^2}{2\sigma^2}\right)$$

where $\|x - x'\|$ is the Euclidean norm between x and x', and d is the dimension of the space R^d.

This KDE approach was particularly interesting to apply in this study because, for data detected over long distances, such as lightning, there could be an intrinsic location error. Thus, it is possible to overcome the error inherent in pinpointing the discharge point in detection networks. The application of KDE can provide valuable initial insights into lightning activity, such as which regions have a higher concentration of lightning events.

3. Results

Figure 4 shows kernel density maps of lightning on an annual scale. The highest concentrations of lightning were recorded in areas to the southwest and northeast of the Itacaiúnas River watershed (IRW). This suggested that storms may be influenced by different land use and land cover types and by the terrain configuration, which exhibits higher elevations of up to 900 m, as seen in the southwest region of the basin (Figure 1).

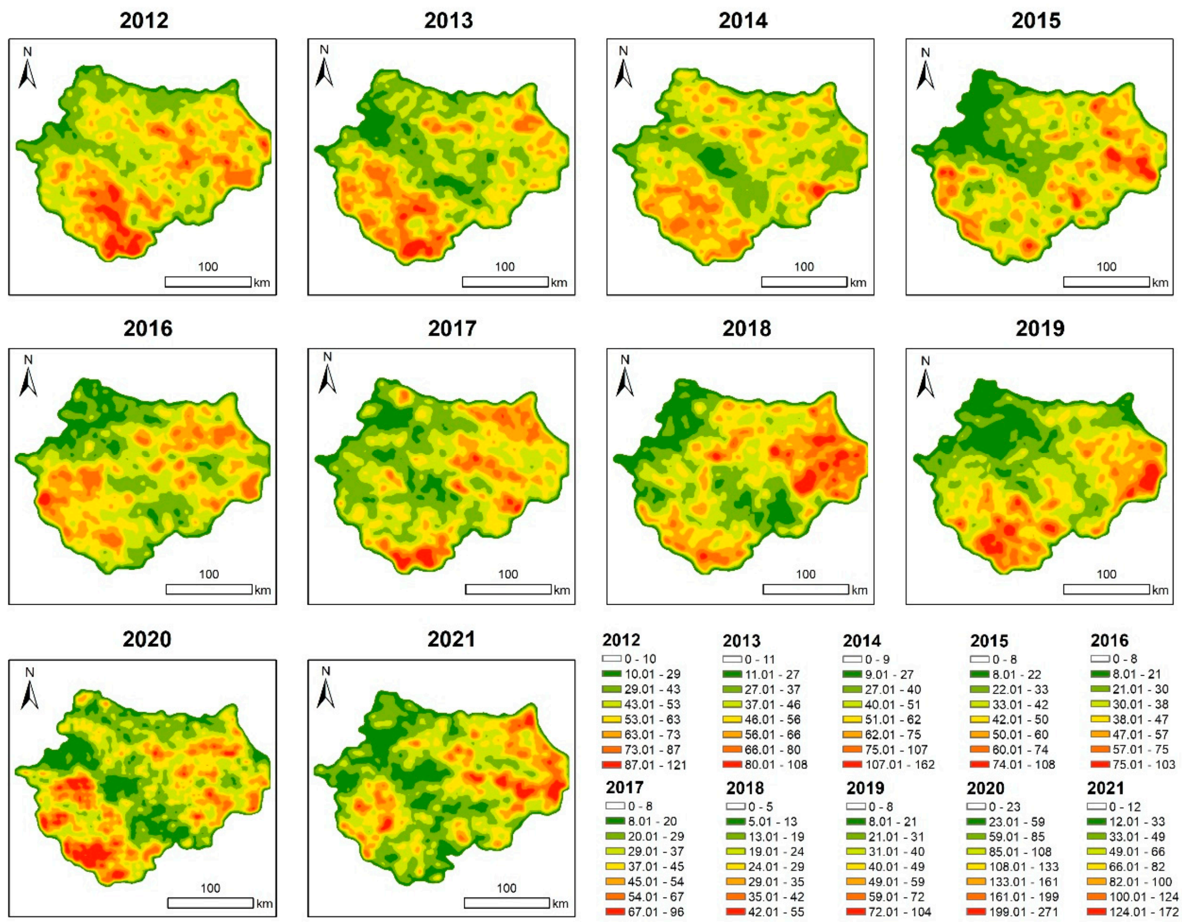


Figure 4. Kernel lightning density (lightning/km^2/year) in the Itacaiúnas River watershed (IRW) from 2012 to 2021. The density scale varies each year. Bandwidth = 7 km.

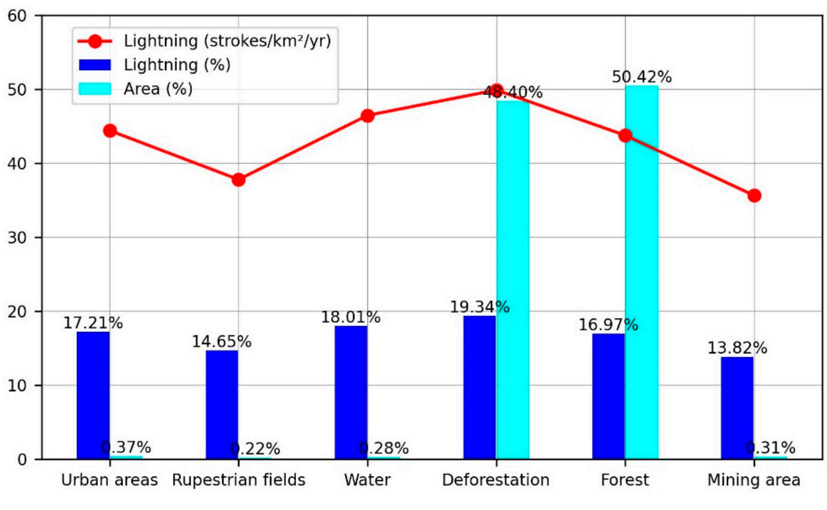
Considering the potential influence of elevation, the formation of convective clouds can be favored because a warm and moist air mass, when encountering a mountain, is forced to ascend due to valley–mountain circulation effects. In this case, cloud formation occurs on the windward side of the mountain (the side from which the wind is blowing), and it is possible that intense rainfall accompanied by lightning may occur.

On the other hand, the lightning observed in the northeast of the region may be associated with the influence of the Intertropical Convergence Zone and/or Instability Lines, potentially intensifying when they encounter deforested areas, as shown in Figure 1. Bare soils are notably warmer, which can enhance convective systems. Additionally, the reduced terrain roughness intensifies wind shear, which can also favor the formation of convective cells with greater vertical development and, consequently, generate lightning. In this case, there is a hypothesis of the influence of land use and land cover on the intensification of storms.

To assess possible relationships with LULC, lightning was counted based on its incidence in different types of land use and land cover in the region. Additionally, a lightning count was conducted for elevation strata to evaluate potential topographical influences. The results are presented in Figures 4 and 5, respectively.

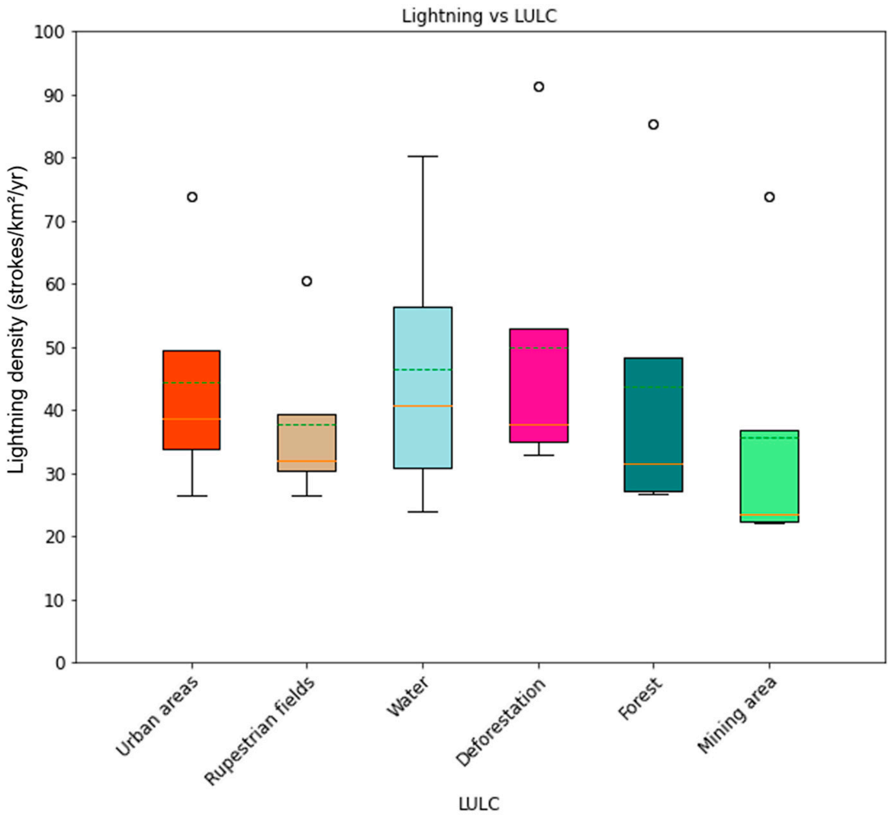
Figure 5 presents the numbers for the average lightning density in different land use and land cover categories and the percentage of occurrence in the IRW area. The highest average lightning density occurred in deforested/pasture areas, with approximately 50 strokes/km^2/year, which corresponded to approximately 19% of the total lightning in the basin. Over water, urban areas, and forests, the lightning density was approximately 18%, 17%, and 16%, respectively. Last, the lowest lightning incidence occurred in rupestrian fields (~15%) and mining areas (~14%).

What stood out in these results was the high occurrence of lightning across the entire IRW, including urban areas and mining areas. In other words, these results suggested a high incidence of lightning in areas with higher population density and in mining areas, which may increase the risk of fatalities caused by this phenomenon. According to a survey conducted by the Atmospheric Electricity Group at the National Institute for Space Research (ELAT/INPE), the state of Pará, where the IRW is located, ranks third in the number of lightning-related deaths. The survey covered the period between 2000 and 2019 and showed that Pará recorded approximately 162 fatalities, ranking only behind São Paulo (327) and Minas Gerais (175) in terms of states [27]. Notably, both São Paulo and Minas Gerais are much more populous than Pará, with population densities approximately five and two times higher, respectively, according to data from the IBGE census [28].



(**a**)

Figure 5. *Cont.*



(**b**)

Figure 5. Lightning density (strokes/km^2/yr) in different land cover types in the Itacaiúnas River watershed (IRW) region (**a**,**b**). In the boxplot (**b**), the solid line represents the 2nd quartile (median), and the dotted line is the mean. The circles represent the outliers.

In mining areas, the favorability of storms can depend on specific factors such as the type of ore extracted, local topography, and regional weather conditions. In the area under study, the high frequency of lightning may occur due to several reasons, such as: (1) mining activities altering the local topography, creating uneven terrain, dams, excavations, and heaps that can affect surface roughness and, consequently, airflow patterns [8]. Additionally, (2) certain activities involving the use of explosives, heavy machinery, and industrial processes that generate heat can create localized heating points and generate updrafts of warm air, which, coupled with the high humidity of the IRW, may contribute to the development of storm clouds [29]. (3) Mining facilities often include metallic structures such as buildings, plants, reclaimers, cranes, rails, and equipment, which can increase the risk of lightning during storms due to their electrical conductivity [30]. (4) Certain activities involving the emission of dust particles and other aerosols into the atmosphere can act as condensation nuclei, promoting the formation of storm clouds and increasing the likelihood of lightning activity [31,32]. Therefore, these changes can contribute to the intensification of storms and lightning activity.

These results underscore the importance of initiatives aimed at protecting both the general population in urbanized areas and workers and equipment. Furthermore, the findings also emphasized the importance of initiatives focused on implementing and/or improving lightning warning systems in mining regions, particularly in reducing production downtime due to storms.

Figure 6 presents the occurrence of lightning by elevation strata. The elevation strata were defined here as low (70 to 300 m), intermediate (301 to 500 m), and high (above 501 m). It was observed that the occurrence of lightning, in general, showed similar values at lower and intermediate elevation levels (approximately 70 to 600 m), with a slight reduction in the range of 601 to 800 m. On the other hand, above the 800 m level, the incidence of lightning resembled that of the lower and intermediate levels.

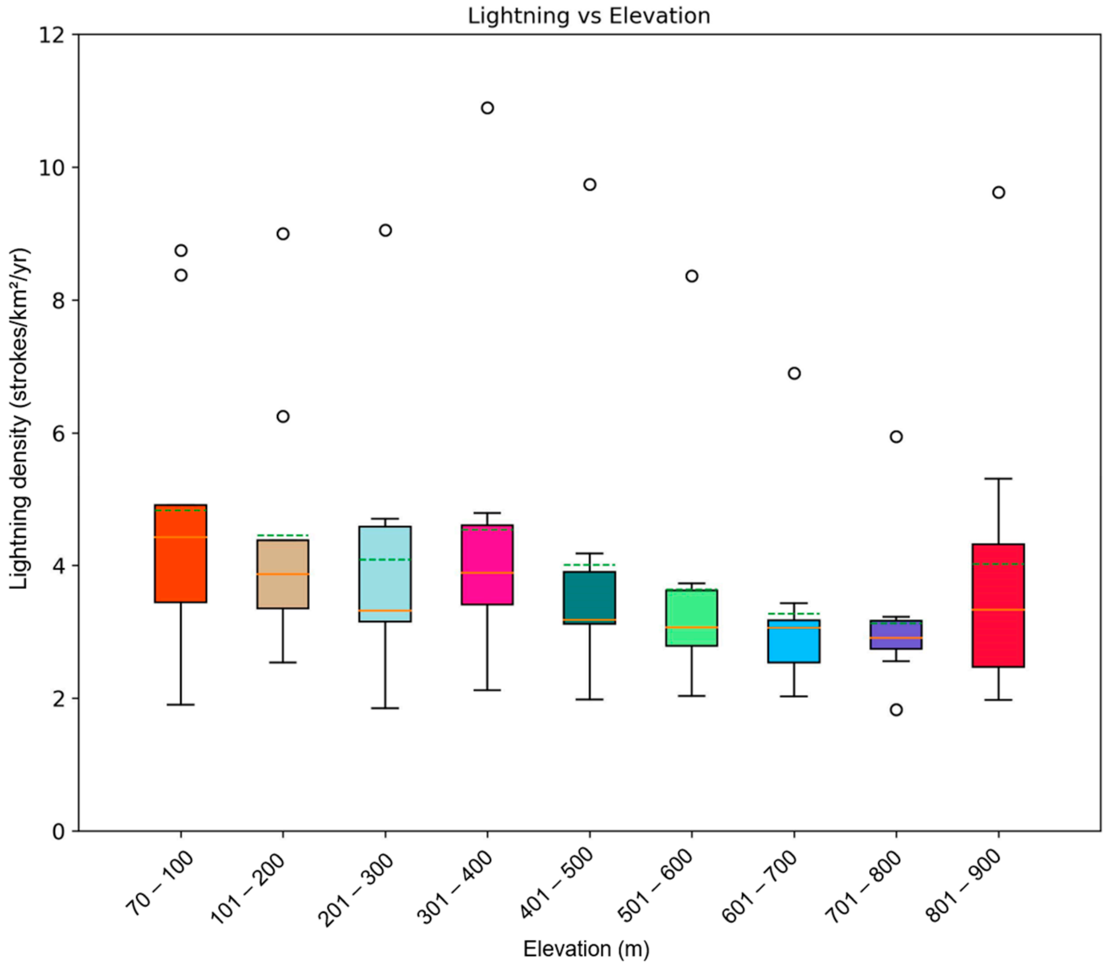


Figure 6. Lightning density in different elevation strata in the Itacaiúnas River watershed (IRW) region. The solid line represents the 2nd quartile (median), and the dotted line is the mean. The circles represent the outliers.

However, it is important to highlight that when evaluating outliers, intermediate elevations tended to show the highest values compared to other elevation strata. This indicated that electrical activity in the region may be related to the terrain slope rather than just the altitude. Orographic lifting tends to form convective clouds over elevated terrains but not necessarily over the highest parts of the region, as illustrated in Figure 7. Spatial interaction of inclined terrain with the endpoints of a lightning strike (leader) approaching the ground can produce many options for ground connection, as the elevated electric field can increase the probability of multiple connections between the lightning and the ground.

Other approaches regarding this matter [13] have already shown that in cases where there is a terrain gradient (different from local roughness), conditions are created for the production of more options for the attachment of lightning branches to the ground. This effect may be associated with spatial variations in the electric field near the surface, caused by variations in the height/slope of the surface's electric boundary condition. This would produce competing areas of higher and lower electric fields near the surface during lightning propagation toward the ground. These results aligned with what was observed by [12,33] regarding CG lightning incidences in Southern Brazil, suggesting that terrain slope may have more influence than altitude on lightning activity.

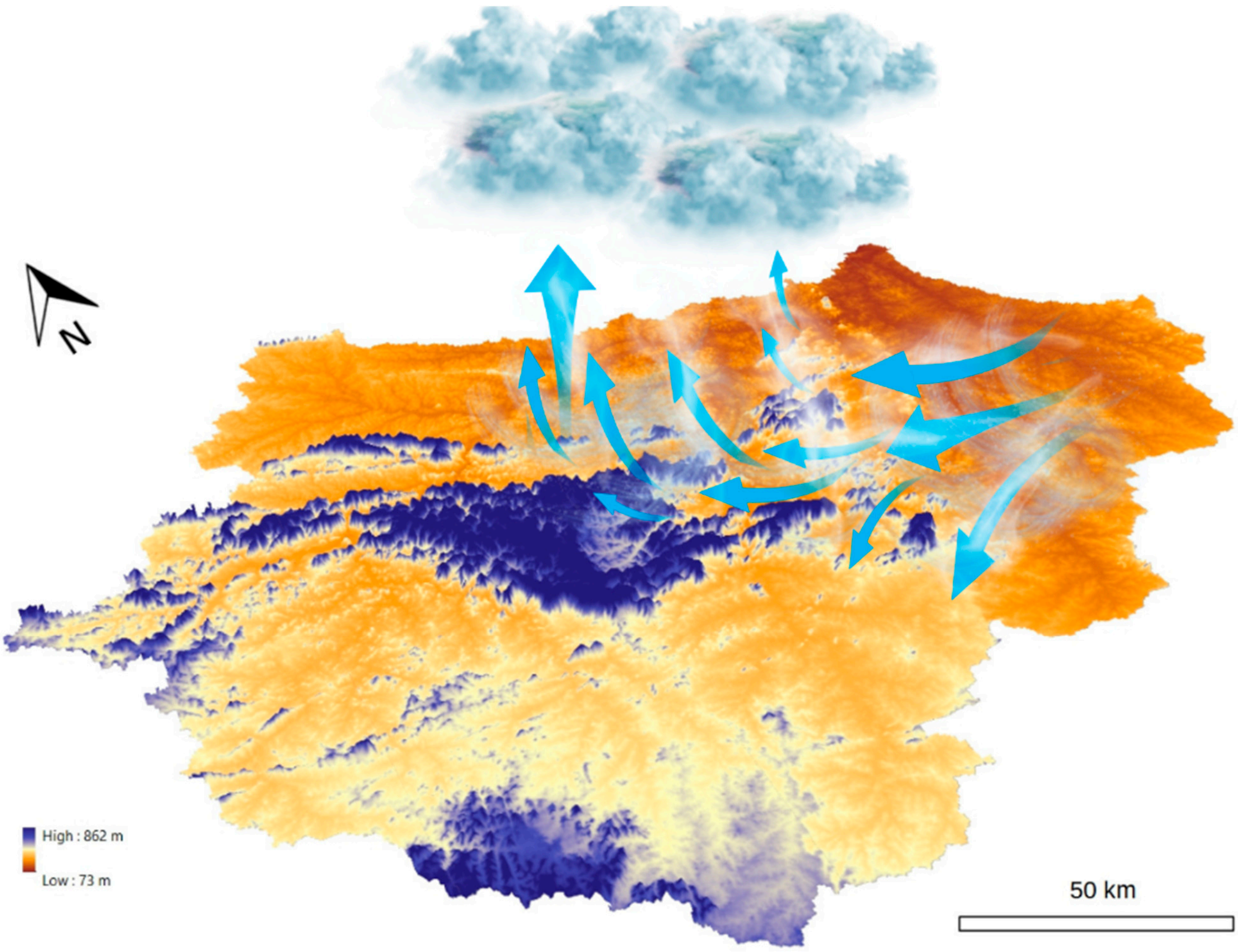


Figure 7. Illustration scheme of the predominant wind direction and orographic cloud formation in the Itacaiúnas River watershed (IRW). The prevailing wind direction information refers to the annual climatology for the 30-year period between 1991 and 2020 from ERA5.

4. Conclusions

In the present study, a survey on lightning activity in the Itacaiúnas River watershed (IRW) region in the Carajás Mineral Province in the Eastern Amazon for the period from 2012 to 2021 was conducted. The aim was to assess the possible influences of lightning activity with different land use and land cover types, as well as to evaluate the incidence of lightning in different elevation strata in the region.

The results revealed peculiarities between different land use and land cover types, among which forested and deforested areas accounted for nearly 99% of the IRW. Despite this territorial dominance, the difference in the percentage of lightning incidence in relation to other areas was very small. Between mining and deforested areas, with the lowest and highest territorial occupation, respectively, the difference in the percentage of lightning was 5%. That is, the average lightning density over the study region is high and presents small percentage variations across different land use and land cover types. This study has highlighted the factors that may contribute to the high electrical activity in mining areas, as it is the main focus of this study. However, further investigations are needed.

The assessment of electrical activity in different elevation strata showed that lightning may be more related to the terrain slope (orographic lifting) than altitude per se, and this may be associated with the spatial interaction of inclined terrain with the endpoints of a lightning strike approaching the ground, which can produce multiple options for ground connection. This is because, with the elevated electric field, there is a possibility of increasing the probability of multiple connections between the lightning and the ground.

In both analyses, the results revealed a high incidence of lightning in the IRW and highlighted the importance of initiatives aimed at protecting the lives of workers and equipment exposed to the open sky in this region.

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