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Authors: Fernando Augusto Díaz-Ortiz and Francisco José Román-Campos

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Correlation between surface air temperature andlightning events in Colombia

Correlación entre temperatura superficial del aire y eventos de rayos en Colombia

Fernando Augusto Díaz-Ortiz[1] https://orcid.org/0000-0002-7989-3475 Francisco José Román-Campos[2] https://orcid.org/0000-0001-9500-4060

[1]Programa de Ingeniería Electrónica, Universidad de Cundinamarca. Diagonal 18 # 20-29. C. P. 252211. Fusagasugá, Colombia.
[2]Departamento de Energía, Eléctrica y Electrónica, Universidad Nacional. Avenida Carrera 30 # 45-3. C. P. 16486. Bogotá, Colombia.

Corresponding author: Fernando Augusto Díaz-Ortiz
E-mail: faugustodiaz@ucundinamarca.edu.co

Abstract: This paper presents findings on the correlation between surface air temperature and lightning activity in Colombia. The air temperature data spans several decades, while the lightning data covers 17 years. The temperature records come from nine cities, and the lightning data covers about 50% of the territory. Despite differences in sampling rates and dataset sizes, the findings show a positive correlation between surface air temperature and lightning activity, suggesting a possible relationship between warmer conditions and increased lightning activity.

Keywords
Lightning; air temperature; greenhouse gases; aerosols; Colombia
Rayos; temperatura del aire; gases de efecto invernadero; aerosoles; Colombia

Resumen: Este artículo presenta hallazgos sobre la correlación entre la temperatura del aire en superficie y la actividad de rayos en Colombia. Los datos sobre la temperatura del aire abarcan varias décadas, mientras que los datos sobre los rayos cubren 17 años. Los registros de temperatura provienen de nueve ciudades y los datos de rayos cubren alrededor del 50% del territorio. A pesar de las diferencias en las tasas de muestreo y el tamaño de los conjuntos de datos, los hallazgos muestran una correlación positiva entre la temperatura del aire en la superficie y la actividad de los rayos, lo que sugiere una posible relación entre condiciones más cálidas y una mayor actividad de los rayos.

1. Introduction

A collaborative effort between the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Agency (JAXA) produced the Tropical Rainfall Measuring Mission (TRMM) [1]. This mission had instruments to measure temperatures and gases in the atmosphere, as well as optical instruments to register lightning activity by detecting optical emissions from cloud tops during thunderstorms. The mission operated successfully for 17 years until 2015, when the satellite was turned off. However, the system had limitations due to varying accuracy between day and night and the short observation time over specific regions.

Lightning is a phenomenon that occurs when discharges happen between electrical charge centers within or between clouds [2]. The formation of these charge centers is complex and not yet fully understood, a process known as cloud electrification. Only one type of cloud, the cumulonimbus, can generate the right conditions for lightning. This cloud has significant vertical development, reaching the upper limits of the troposphere. Inside this large structure, strong gusts of wind and random collisions between hydrometeors (water in different states, from liquid to solid) seem responsible for its electrification. Once the charge centers are established, an electrical discharge can occur. However, the exact conditions necessary for lightning inception are still unknown.

Given that water is essential for cloud formation, understanding the Earth's hydrological cycle is crucial to comprehending cloud formation, electrification, and lightning occurrence. The hydrological cycle is primarily driven by the heat provided by the sun in a specific region [3]. The focus then shifts to the effect of warmer conditions on this cycle, raising the question of whether higher temperatures could increase or decrease the number of thunderclouds responsible for lightning activity[4].

Theories currently point in both directions. Some suggest that warmer conditions will increase the frequency of lightning activity worldwide. In contrast, others argue that a hotter Earth would reduce the amount of available water, decreasing the number of thunderstorms [5]. However, some studies propose that fewer thunderstorms could result in more intense lightning activity [6]. In any case, predicting the future of lightning in a warmer world is challenging due to its complex nature and dependence on numerous conditions [7]. Accurate forecasts must consider multiple factors and rely on advanced meteorological models and extensive lightning record analyses to establish trends [8].

The study of lightning activity in Colombia is justified by the high levels of activity reported by various measurement stations. Colombia consistently ranks high in these reports. For example, according to several studies, Colombia holds twenty positions among the 500 lightning hotspots on Earth, making it the third country with the most places on this list, preceded only by nations in the Congo Basin (the Democratic Republic of Congo and the Central African Republic) [5]. According to the paper's methodology, these lightning hotspots are interpreted as areas rather than single points. Approximately 160,000 km^2 (around 14% of Colombian territory) experience very high lightning activity.

2. Climate and lightning in Colombia

2.1 Greenhouse gases and aerosols effect

Solar radiation is the ultimate energy source influencing all weather and climate phenomena on Earth. Some incoming radiation is immediately reflected into space, while the remaining energy is absorbed by the atmosphere, land, and oceans through various natural mechanisms [9]. This process creates an energetic balance that drives all natural phenomena on Earth. Atmospheric gases, particularly naturally occurring greenhouse gases, trap much of this energy by absorbing and re-emitting infrared radiation. These gases, including water vapor, carbon dioxide (CO2), ozone (O3), and methane (CH4) [10], play a crucial role in maintaining the planet's energy balance, preventing freezing temperatures.

The actual problem arises when the balance of these gases changes due to human activity, raising deep concerns about the implications for Earth's climate. In addition to gases, the atmosphere contains aerosols from both natural and human-related sources, such as desert dust, sea salt, volcanic ash, wildfires, and fossil fuel burning [11]. Earth's atmosphere is a massive mixture of gases and aerosols that can be influenced by natural and human activities. These particles, in solid, liquid, or gaseous phases, are significant because they affect Earth's energy balance in two major ways: i) absorbing and scattering solar radiation back into space, and ii) acting as nuclei for cloud droplet formation. Consequently, their presence or absence can impact natural phenomena.

2.2 Relationship between air surface temperature and lightning

According to the Fourth and Fifth Intergovernmental Panels on Climate Change (IPCC), increases in carbon dioxide and other greenhouse gases have almost certainly contributed significantly to the observed temperature rises in the 20th century. Specifically, results from over twenty three-dimensional climate models presented in the report indicate that with drier surfaces and warmer climates, lightning activity will increase. The most significant potential impacts of climate warming are changes and intensification of extreme weather events . These events pose a concern due to their impact on populations, infrastructure, and other activities, potentially causing significant loss of life and resources. Models predict that extreme weather events will vary globally[10].

Several climate simulations suggest a 10% increase in global lightning activity for each degree of global warming, with the most significant growth in the tropics. This trend is likely related to one key element for generating thunderstorms: the presence of humid, warm air that can rise rapidly, creating powerful updrafts. These updrafts carry humidity to high altitudes where temperatures are well below freezing, forming powerful thunderclouds.

2.3 Geophysical Characteristics of Colombia

Colombia is located in the northwest of South America, covering an area of 1,141,748 km² and is home to almost 50 million inhabitants [12]. It has six main natural regions: the Andean, Caribbean, Pacific, Llanos (plains), and Amazon regions. Most of Colombia's population lives in cities within the Andean and Caribbean regions. The Andean region features three mountain chains. The northern part of the Andes mountains creates a complex terrain of inter-Andean valleys and hills. Notably, some of the world's highest lightning density areas are in northern Colombia, linked to the seasonal variation of trade winds associated with the Intertropical Convergence Zone (ITCZ) oscillation and unique topography. Figure 1 shows a map of Colombia marking its global position and details of its particular topography.

Topography is crucial because lightning activity is more likely over land than oceans. This is because air heats faster over land, which cannot store as much energy as oceans. Consequently, hot, humid air over land rises quickly, carrying water above freezing levels, and creating conditions for cloud formation and electrification. Therefore, the relief of a region significantly influences strong convection processes.

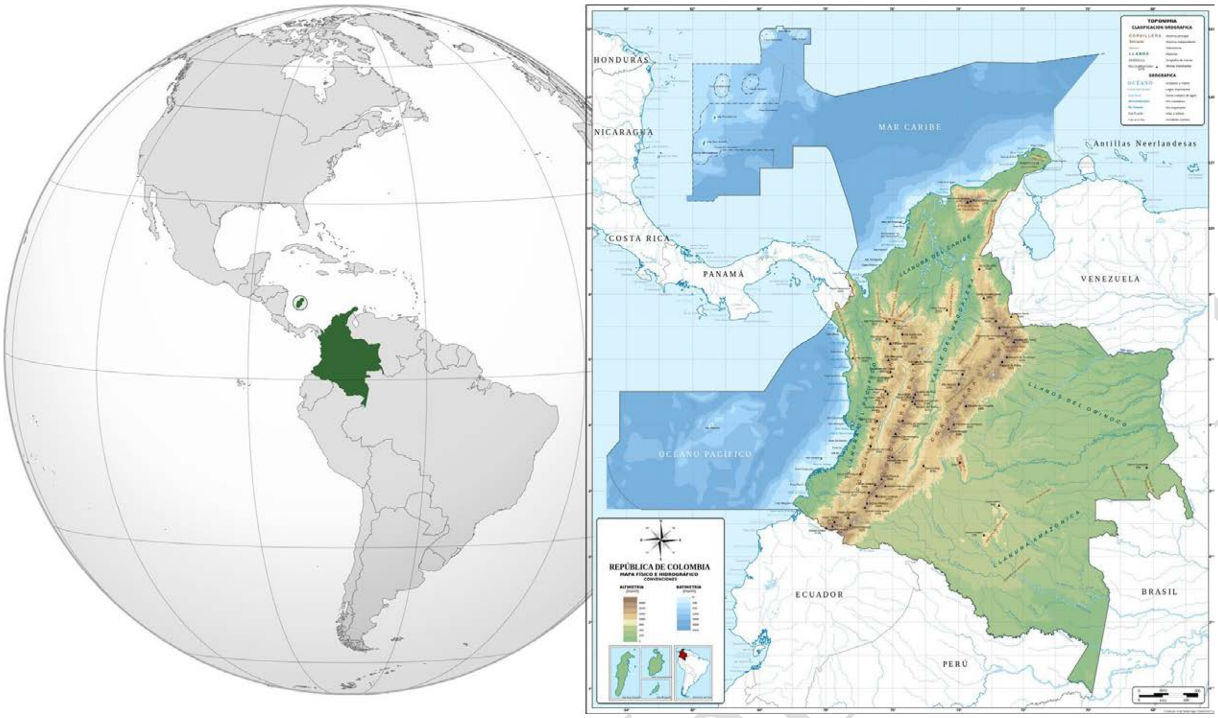

Figure 1 Basic cartography map of Colombia. Source: Instituto Geográfico Agustín Codazzi

3. Methodology

3.1 Datasets

This study used satellite data for a region bounded by the coordinates 77° W, 1° N, 72° W, and 11° N. This selection facilitates future comparisons with ground-based lightning data currently under study. The observation area covers 605,788 km² (about 53% of Colombia's territory), including the Andean region and parts of the Pacific and Caribbean regions. Notably, this area is home to almost 83% of Colombia's population. For this study, lightning activity data was obtained from the TRMM mission [13] [14], and surface air temperature records were sourced from the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) of Colombia.

Lightning data comes from a sensor that monitors background radiances continuously to detect optical transients (i.e., optical emissions from the tops of clouds). The sensor had a total field of view of 500 × 500 km² with a detection efficiency of 90-95%. Using this data, the Lightning and Atmospheric Electricity Research group at the Global Hydrology Resource Center has processed and delivered lightning activity data since 1998 [15]. Figure 2 shows the total number of flashes detected over Colombia in 2014.

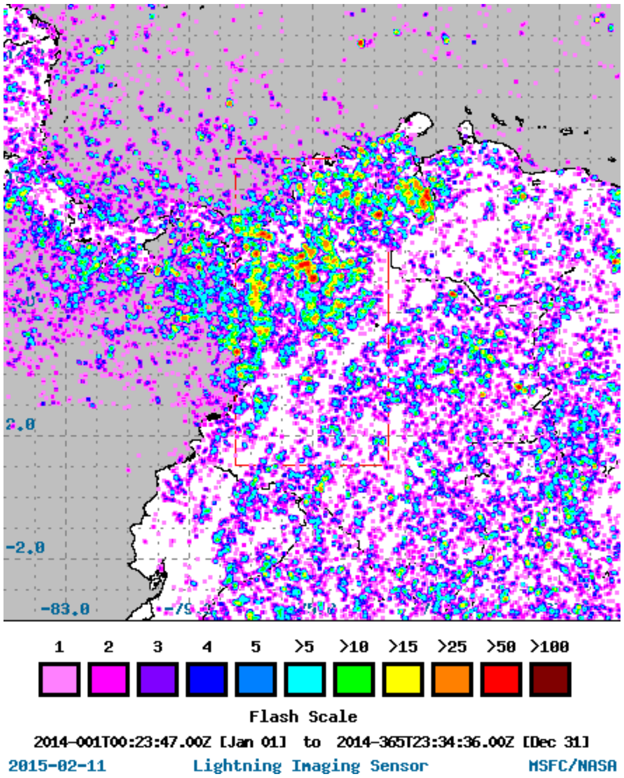

Figure 2 Flashes events detected by LIS/TRMM in 2014 over Colombia. Source: Authors

3.2 Data analysis

This study used a time series of surface air temperature for nine Colombian cities. The temperature data spans three or more decades to better identify possible trends, with the values representing the mean annual surface air temperature for each city. Annual averages were computed from monthly records. A summary of the cities studied and their corresponding observation periods is shown in Table 1.

Table 1 Detail about data availability on surface air temperature

City	Observation period	Years
Barranquilla	1966-2014	38
Bogotá	1961-2014	43
Bucaramanga	1977-2014	37
Cali	1951-2014	53
Cartagena	1951-2014	53
Medellín	1941-2014	63
Villavicencio	1961-2014	43
Santa Marta	1975 -2014	39

Lightning data comes from the TRMM database, which provides records for the previously delimited area. To calculate the total number of lightning flashes for each year, monthly values were summed. These observations were used to create a time series of the total number of flashes for the study area. The lightning data covers 17 years, from 1998 to 2014, but lacks sufficient resolution for city-specific time series, so the comparison is made between the local time series for surface air temperature and the total lightning activity for the area.

The analysis involved identifying trends and assessing the relationship between the time series data. While identifying a relationship does not yield conclusive results, it can highlight elements for further research. A confidence interval was used to assess the existence of a linear relationship between the two time series, and linear regression analysis tested for linear trends. Finally, a t-test determined if the slope of the regression line was statistically different from zero.

4. Results

Figure 3 shows the monthly time series of flashes detected along with its corresponding linear fitting function. The graph illustrates a general increase in events detected by the satellite, rising from nearly 10,000 events in 1998 to over 12,000 events in 2014. This represents an increase of approximately 20% in lightning events in this part of the country. It is important to note that these numbers represent flash occurrences during the satellite's passage over the region; therefore, 10,000 events are just a small sample of the total flash population in the country. Ground-based instrumentation estimates the annual number of flashes in Colombia to be around 16 million, meaning that low-orbit satellite data represents less than 1% of the estimated population. Nonetheless, the long observation period of the satellite data makes it valuable.

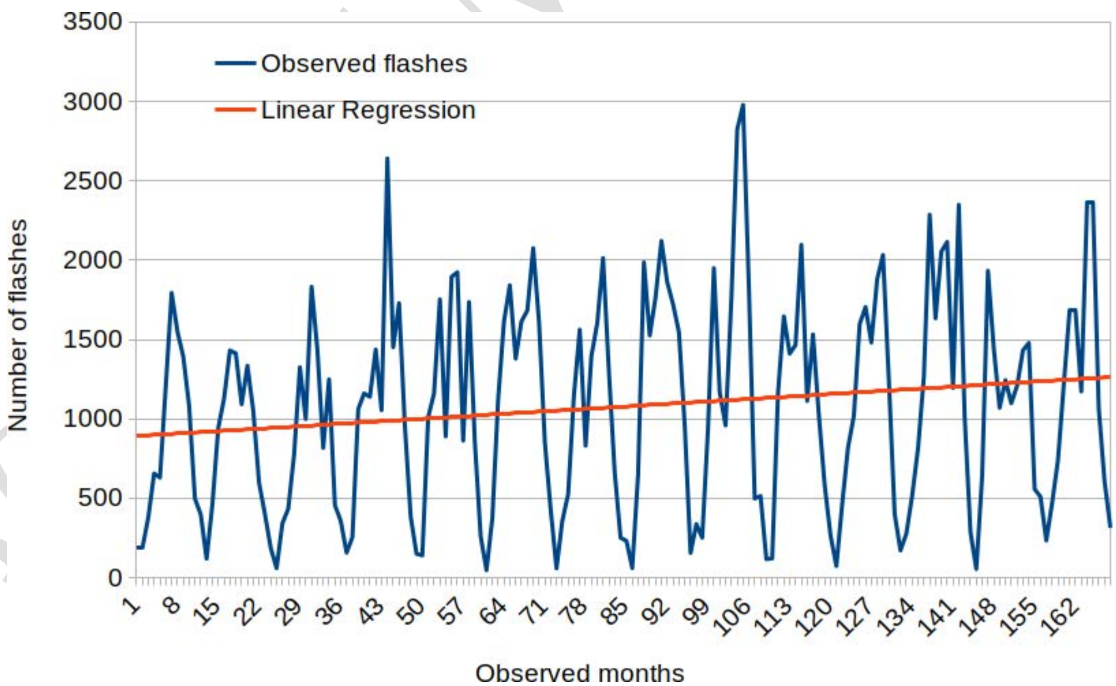

Figure 3 Time series of the total annual number of flashes detected from 1998 to 2014 over Colombia by LIS instrument. Source: Authors

Figure 4 shows the behavior of the average annual temperature in nine Colombian cities over the last few decades by calculating and plotting annual values and fitting a linear function to the data. A clear trend of increasing temperatures is evident in all cities. On average, these cities are about 1°C hotter than they were forty years ago. While this increase may seem small, it represents a significant change. For Bogotá, this increase translates to a 10% rise in average temperature, while for other cities, the increase represents only about 1%.

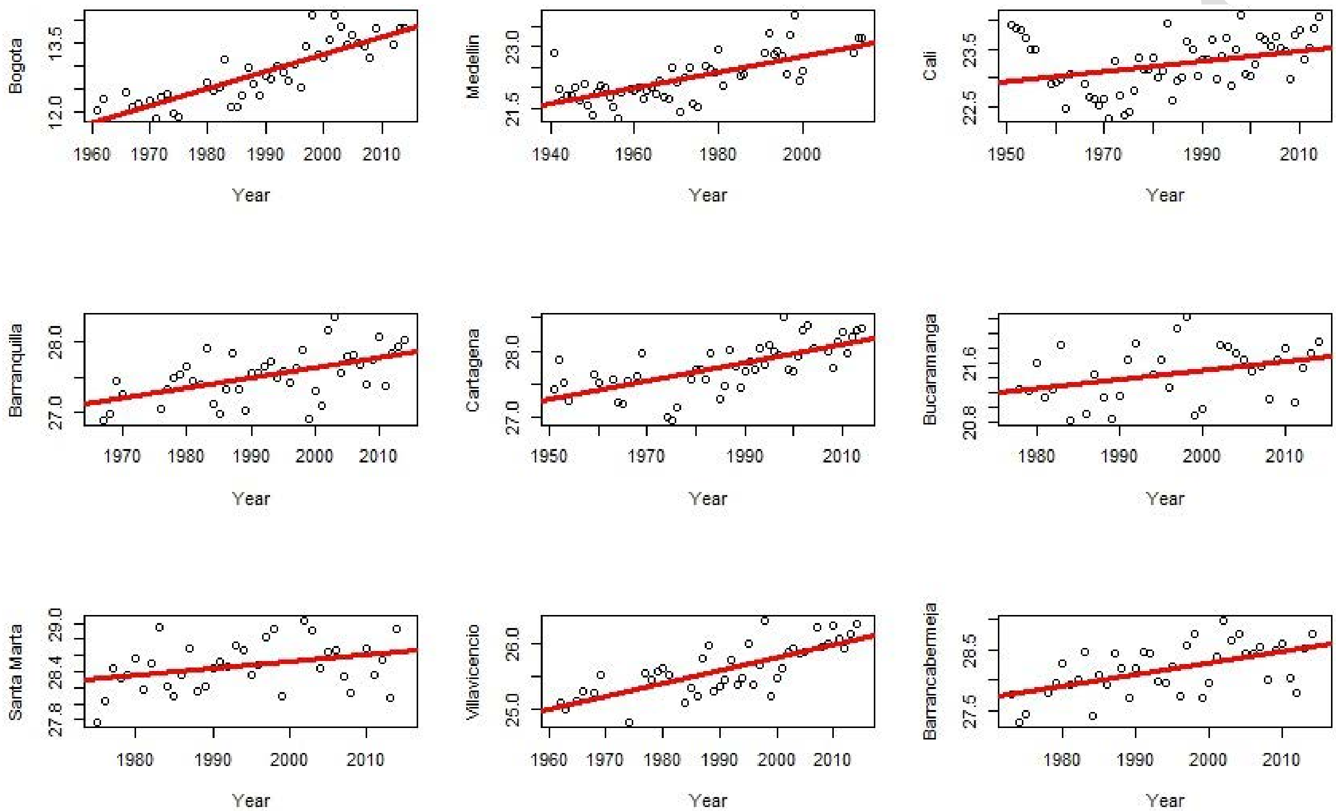

Figure 4 The figure shows a surface air temperature time series of 17 years with its corresponding simple linear regression model for nine Colombian cities. Without exception, all cities show an increasing trend in their average surface temperature. Source: Authors

Table 2 presents the cross-correlation results between flash activity and surface temperature using equal time windows. Undersampling data can impact cross-correlation calculations, often producing higher values than those obtained with more samples. Therefore, the data in Table 2 should be used as a reference, with the understanding that precise values might be lower; however, the trend in the relationship between the time series will remain the same.

Table 2 Summary of cross-correlation results of the time series of surface air temperature versus flash activity

Air surface temperature vs lightning activity	**Pearson**	**P-value**
Barrancabermeja	0.5578	0.00031
Barranquilla	0.5456	0.00015

Bogotá	0.8538	1.75e-13
Bucaramanga	0.3507	0.042
Cali	0.3463	0.00671
Cartagena	0.6740	1.5e-07
Medellín	0.7047	2.7e-09
Santa Marta	0.3331	0.0439
Villavicencio	0.7562	6.93e-09

5. Conclusions

The apparent increase in temperature is difficult to explain with the available data. However, every city in this study has experienced rapid population growth and drastic changes in the urban landscape over the last 50 years. Therefore, the heat island phenomenon is a plausible explanation for the rise in surface air temperature. Due to buildings, houses, and streets, heat islands absorb and retain more energy, which can reduce average temperature changes.

The findings suggest a warming trend in all the Colombian cities under study, with an average temperature rise of 0.64°C over the last 40 years. The causes of this trend and their possible implications will remain topics for future research and discussion. As mentioned earlier, the heat island effect is one possible explanation, but the generation of aerosols due to human activities could also account for this trend.

Another possible explanation for the apparent temperature increase is changes in land cover. In these cities, environmental conditions have shifted due to deforestation and the depletion of water supplies, making many areas drier. To confirm a generalized increase in surface air temperature, it is necessary to consider data from rural regions where the landscape has remained relatively unchanged. The authors of this study are currently working on this topic to obtain more reliable conclusions.

Regarding lightning activity, the apparent increase in frequency could be related to a warmer climate. However, this hypothesis requires more in-depth studies for validation. One consequence of this increase is a greater threat to infrastructure and living beings. This is particularly relevant for Colombia, which has regions with high flash rates and significant populations and infrastructure. In this context, the apparent rise in lightning activity underscores the need for improved lightning protection equipment.

6. Declaration of competing interest

We declare that we have no significant competing interest, including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

7. Acknowledgments

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9. Author contributions

Francisco Román designed the study. Fernando Díaz-Ortiz carried out the analysis and wrote the article.

10. Data availability statement

Data will be made available on request.

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