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Mapping the lightning hotspot : reducing deaths in Jharkhand, India, using spatiotemporal and statistical insights

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सार – यह शोध भारत के झारखंड राज्य में तड़ित क्षणदीप की स्थानिक-कालिक परिवर्तिताओं विशेष रूप से इंट्रा क्लाउड (IC), नकारात्मक बादल से जमीन (NCG) और सकारात्मक बादल से जमीन (PCG) की जांच करता है। भू-संदर्भित तड़ित के वास्तविक आंकड़े (IC, NCG, और PCG) भारतीय उष्णकटिबंधीय मौसम विज्ञान संस्थान (IITM) के लाइटनिंग लोकेशन नेटवर्क (LLN) सेंसर से एकत्र किए गए जिसे 2019-2023 के दौरान भारतीय उपमहाद्वीप में तैनात किया गया था। इसके अनुरूप झारखंड सरकार के गृह, जेल और आपदा प्रबंधन विभाग ने अध्ययन की अवधि के लिए तड़ित से संबंधित हताहतों का डेटा प्रदान किया। झारखंड का विविध भूगोल, जिसमें पहाड़ियां, पठार और वन शामिल हैं जो विशेष रूप से प्री-मॉनसून पूर्व (मार्च से मई) और मॉनसून (जून से सितंबर) ऋतु के दौरान गरज के साथ तूफान और तड़ित गिरने के लिए अनुकूल परिस्थितियां पैदा करता है। नम वायुराशियों की ये अवधि वायुमंडलीय अस्थिरता से चिह्नित होती है जिससे तड़ित गिरने की संभावना बढ़ जाती है। ग्रामीण क्षेत्रों में पर्याप्त तड़ित संरक्षण प्रणालियों और सुरक्षा प्रोटोकॉल के बारे में जागरूकता का अभाव है जो विशेष रूप से संवेदनशील है तथा गरज के साथ तूफान के दौरान जोखिम बढ़ जाता है। अध्ययन में तड़ित के आंकड़ों का विश्लेषण करने के लिए अंतर्वेशन विधियों सहित स्थानिक-कालिक सांख्यिकीय तकनीकों का उपयोग किया गया। भू-स्थानिक ताप मानचित्र झारखंड के तड़ित के हॉटस्पॉट में तड़ित गिरने की घटनाओं और उससे जुड़ी दुर्घटनाओं की स्थानिक-कालिक परिवर्तिताओं को दर्शाते हैं। इस शोध में मौसमी तड़ित की प्रवर्त्ति, स्थान-विशिष्ट संवेदनशीलता, अस्थायी खतरों और संबंधित मौसम संबंधी कारकों की व्यापक जांच की गई है।

इसके अलावा, शोध पत्र में झारखंड में आपदा की तैयारियों को बढ़ाने के लिए रणनीतियां प्रस्तावित की गई हैं जिसमें दूरदराज के क्षेत्रों में मौसम संबंधी निगरानी और पूर्व चेतावनी प्रणाली को मजबूत करने की आवश्यकता पर जोर दिया गया है। तड़ित सुरक्षा ज्ञान व तैयारियों में सुधार के लिए किसानों और जनजातीय समुदायों जैसे कमजोर समूहों पर लक्षित जन जागरूकता अभियान बहुत महत्वपूर्ण हैं। सामुदायिक लचीलापन-निर्माण पहलों जैसे आपदा प्रबंधन प्रशिक्षण और आपातकालीन प्रतिक्रिया योजना में स्थानीय भागीदारी की सिफारिश की जाती है ताकि तड़ित गिरने के प्रभावों को प्रभावी ढंग से कम किया जा सके।

ABSTRACT. This research investigates the spatial and temporal variations of lightning flashes, specifically in-tra-clouds (IC), negative cloud-to-ground (NCG) and positive cloud-to-ground (PCG) strikes, across the state of Jharkhand, India. Actual georeferenced lightning data (IC, NCG, and PCG) were collected from the Indian Institute of Tropical Meteorology's (IITM) Lightning Location Network (LLN) sensor deployed over the Indian subcontinent during 2019–2023. Corresponding the Department of Home, Jail, and Disaster Management, Govt. of Jharkhand, provided lightning-related casualty data for the studied periods. Jharkhand's diverse geography, encompassing hills, plateaus, and forests, creates favorable conditions for the development of thunderstorms and lightning strikes, particularly during the pre-monsoon (March to May) and monsoon seasons (June to September). These periods of moist air masses are marked by atmospheric instability, increasing the likelihood of lightning strikes. Rural areas, lacking adequate lightning protection systems and awareness of safety protocols, are especially vulnerable, posing risks to lives and property during thunderstorms. The study employs spatiotemporal statistical techniques, including interpolation methods, to analyze lightning data. Geospatial heat maps illustrate the spatial and temporal variability of lightning occurrences and associated casualties in Jharkhand's lightning hotspots. The research comprehensively examines seasonal lightning patterns, location-specific susceptibility, temporal hazards, and related meteorological factors.

Furthermore, the research proposes strategies to enhance disaster preparedness in Jharkhand, emphasizing the need for strengthened meteorological monitoring and early warning systems, particularly in remote areas. Public awareness campaigns targeted at vulnerable groups such as farmers and tribal communities are crucial to improving lightning safety knowledge and preparedness. Community resilience-building initiatives, including disaster management training and local involvement in emergency response planning, are recommended to mitigate the impacts of lightning strikes effectively.

Key words – Lightning, Lightning-related casualty, C-G lightning, Jharkhand, Lightning safety.

1. Introduction

Lightning strikes, an electrically hazardous phenomenon, have the potential to result in forest fires, transportation accidents, telecommunications disruptions, and most important loss of life among both humans and animals (Kumar and Kamra, 2012; Qie *et al.*, 2021). Lightning, (López *et al.*, 2022) a potent and capricious weather phenomenon, has the potential to be lethal (Rabbani *et al.*, 2022). There are very few records of lightning-related fatalities, the regional and national dispersion of lightning flashes has been investigated using the LLN in India (Cecil *et al.*, 2014; Jayawardena *et al.*, 2014; Mishra *et al.*, 2022; Shankar *et al.*, 2024; Yadava *et al.*, 2020). The majority of lightning strikes, around 80%, are observed in tropical regions(Christian *et al.*, 2003; Holle and Murphy, 2017). The equatorial trough and dry line between dry and moist winds are responsible for the concentration of global lightning activity in South Asian countries (Singh and Singh, 2015). Emerging nations such as India, Bangladesh, Pakistan, Sri Lanka, and Nepal face significant public health and safety risks due to disasters caused by lightning. Throughout history, the regions of Madhya Pradesh, Maharashtra, West Bengal, Kerala, Jharkhand, Karnataka, Bihar, and Odisha have exhibited the highest incidence of lightning-related fatalities (Singh and Singh, 2015). Extensive lightning studies have been conducted worldwide in recent decades (Cecil *et al.*, 2014; Doljinsuren and Gomes, 2015; Gomes, 2017; Nastos *et al.*, 2014; Zhang *et al.*, 2011). A recent study has examined the effect of lightning, atmospheric, and geophysical factors on the distribution of lightning in India (Ahmad and Ghosh, 2017; Das *et al.*, 2015; Nastos *et al.*, 2014; Shankar *et al.*, 2024). The study conducted by (Dewan *et al.*, 2017) investigated the influence of convective available potential energy (CAPE) on the occurrence of lightning. The researchers utilized ERA-40 reanalysis data and Tropical Rainfall Measuring Mission (TRMM) monthly products for both total and convective rainfall. The correlation between lightning activity in Bangladesh and CAPE was found to be statistically significant across various timescales, including monthly, seasonal, and yearly. (Sonnadara *et al.*, 2019) Have demonstrated that sea surface temperature can serve as a reliable indicator for changes in lightning activity in the Arabian Sea and Bay of Bengal, owing to its consistent temporal characteristics (Yadava *et al.*, 2020) calculated a global mortality rate of 0.2-1.7 deaths per million due to lightning. The (Lightning Imaging Sensor (LIS)/TRMM)) data show that between March and April, there were a significant number of lightning strikes in India (Manohar *et al.*, 1999). The greatest flash density per km^2/year in April is 15, which is equivalent to 0.5 km^2/day. (Unnikrishnan *et al.*, 2021) used TRMM and the ground-based Indian Lightning Detection Network to locate significant lightning in South India, which had a significant spatial variation in intense lightning occurrences. Research on lightning in India has been focused on the Central, Northeast, and Himalayan regions (Damase *et al.*, 2021; Murugavel *et al.*, 2014; Penki and Kamra, 2013; Qie *et al.*, 2003). The occurrence of recent fatalities caused by lightning has garnered the interest of policymakers and disaster managers (Michibata, 2024). According to the findings of (Mäkelä *et al.*, 2014) in Nepal and (Dewan *et al.*, 2017) in Bangladesh, there has been a notable rise in lightning occurrences in the region during the pre-monsoon and monsoon seasons.(Holle *et al.*, 2019) investigated the relationship between lightning deaths and agricultural data to ascertain the sensitivity to lightning. The research revealed that the pre-monsoon season had the highest incidence of lightning-related fatalities, primarily attributed to labor-intensive agricultural practices in some regions. However, the link between lightning activities and the underlying factors contributing to high fatality rates at the national or state level is limited (Gomes and Kadir, 2011; Shankar *et al.*, 2024; Yadava *et al.*, 2020).

The current study specifically focuses on the state of Jharkhand, where various meteorological factors such as pre-monsoon and monsoon seasons, cyclonic events, sea surface temperature, and air convection influence lightning occurrences (Glazer *et al.*, 2021). Understanding the relationship between these weather fluctuations and the factors contributing to cloud-to-ground (C-G) lightning in the region is crucial for identifying areas most prone to lightning strikes. Farmers and tribal communities in hilly areas are particularly vulnerable, as they frequently work in open fields surrounded by tall trees. The primary objective of this research is to pinpoint safer

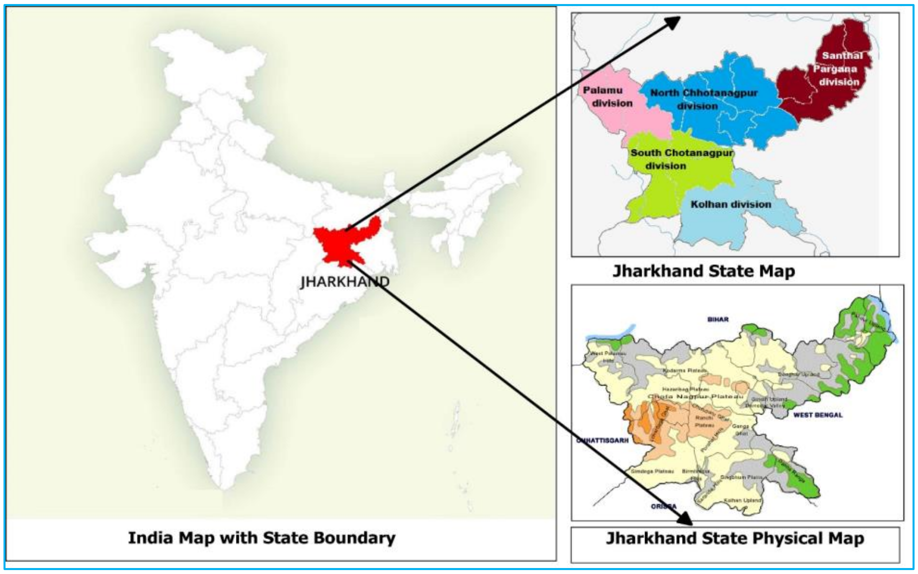


Fig. 1. The state of Jharkhand, situated in eastern India and close to the North Bay of Bengal, and its physiographic and administrative division (*Source* : Govt. of Jharkhand)

locations to protect these populations from lightning hazards. These analyses delved into the spatial and temporal patterns of lightning activity, as well as the underlying factors driving these occurrences. This study aims to provide actionable weather alerts and identify lightning-safe zones for the most vulnerable demographics in the region. This article marks the first exploration of a database comprising lightning flashes (IC, NCG and PCG) sourced from the Lightning Location Network. It aims to investigate the underlying factors contributing to casualties in the vulnerable state of Jharkhand. To enhance understanding and mitigation strategies, the study seeks to identify correlations between these underlying factors and lightning activity. The research outlined below is novel in the following ways:

(*i*) This pioneering study aims to analyze the spatiotemporal patterns of lightning flashes (IC, NCG and PCG) and the underlying contributing factors in Jharkhand, India. It focuses on identifying districts with the highest risk of lightning flashes between 2019 and 2023. The insights gained from this study will address the challenges state officials face in their efforts to prevent lightning-related incidents.

(*ii*) Accurately identifying lightning locations is crucial for issuing precise warnings and forecasts, thereby aiding in risk reduction efforts (Mills *et al.*, 2008). Understanding the spatial and temporal patterns of lightning occurrences and fatalities is essential for effective risk mitigation. This study covers all districts of Jharkhand, analyzing lightning-induced fatalities and flashes over four years (2019-2023).

(*iii*) The findings from this study could inform policymakers and stakeholders about the area’s most vulnerable to lightning-related fatalities, aiding in the development of targeted interventions and strategies for risk mitigation. Additionally, this study adds to the existing body of knowledge by providing comprehensive insights into the specific dynamics of lightning-related fatalities in Jharkhand, potentially informing future research and risk management initiatives in the region.

This paper's subsequent sections follow this structure: Section 2 provides an overview of the study areas, as well as the lightning and associated casualty datasets used. Section 3 elaborates on the methodology employed in this study. Following that, sections 4 and 5 comprehensively present the results and discuss their implications. Finally, Section 6 summarizes the findings and conclusions drawn from this investigation.

2. Study area and data

2.1. *Study Area*

Jharkhand is a state in India's eastern region. The administrative divisions of the state include five major regions: Palamu, north and south Chotangapur, Kolhan, and Santhal Pargana, which have 24 districts. Fig. 1 shows the location of Jhrakhnad's state and physiographic and administrative division. The Chota Nagpur plateau, part of the extensive Deccan plateau, distinguishes the state, spanning 79,716 square kilometers. This terrain features plateaus, hills and valleys, predominantly composed of crystalline rocks. Notably, the coal - bearing

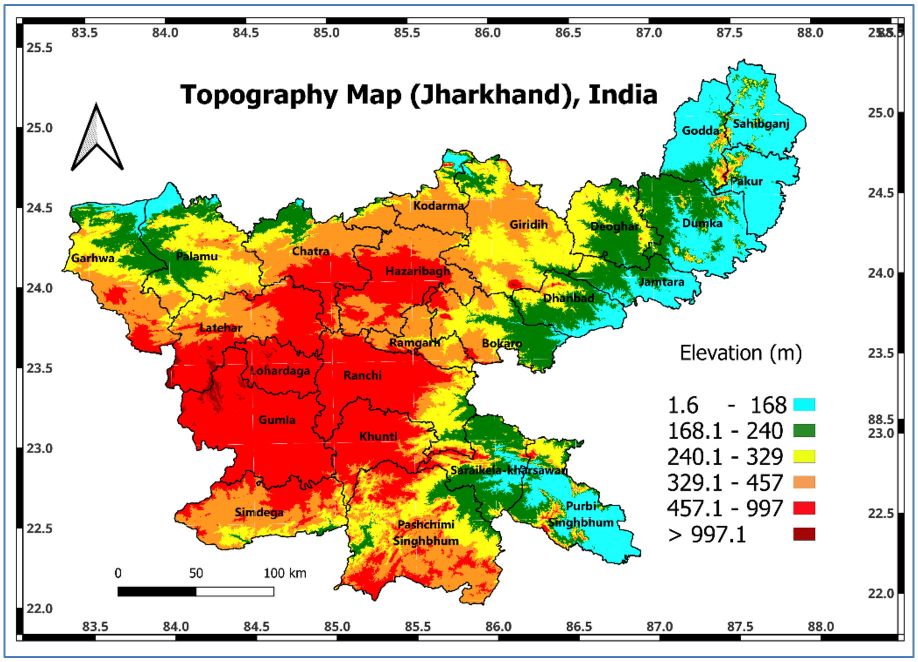


Fig. 2. The topographical map of Jharkhand, India, reveals varying elevations across the state, ranging from less than 2 meters to more than 1000 meters above mean sea level pressure (MSLP). Elevation changes play a crucial role in influencing the occurrence of C-G lightning strikes in the region

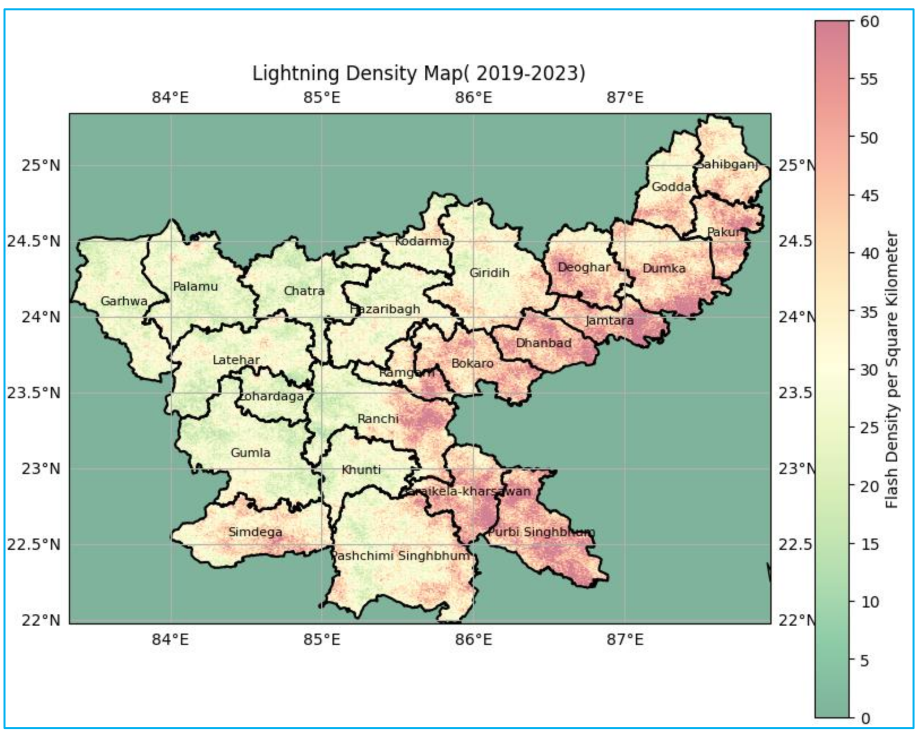


Fig. 3. Illustrates the spatial distribution of the C-G lightning flash density map of Jharkhand during the pe-riod studied, from 2019 to 2023

basin of the Damodar River separates the Hazaribag and Ranchi plateaus, which average about 2,000 feet in elevation. In the west, there are over 300 dissected flat-topped plateaus, some exceeding 3,000 feet. Parasnath Peak, situated on the Hazaribag plateau, rises to a height of 4,477 feet. Rajmahal Hills in the north-eastern region of

TABLE 1

Outlines the details

Data Types	Purpose	Sources
LLN Data	Spatio Temporal Analysis	IITM Pune
Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) Data	Elevation Map (Resolution:30m)	https://earthexplorer.usgs.gov/
Lightning casualty	Lightning fatalities	Department of Home, Jail and Disaster Management, Government of Jharkhand & Media Reports

the state exhibit distinctive geology, vegetation and fauna. The state is drained by rivers such as Damodar in the northeast, Subarnarekha in the southeast, Brahmani in the south, and Son along much of the northwestern boundary. The Damodar Valley has sandy soil, contrasting with the heavier red soils found in plateau regions. Jharkhand is also home to several national parks and wildlife sanctuaries, including the Betla National Park and the Birsa Munda Wildlife Sanctuary, which showcase its rich biodiversity. Fig. 2 presents the detailed topography maps of Jharkhand. The state is one of India's most lightning-prone regions, making it particularly vulnerable during the monsoon season from June to September. The state's rugged hills, plateaus and dense forests significantly contribute to the high incidence of lightning strikes. The updrafts and downdrafts associated with thunderstorms over hilly terrain generate strong electrical charges, making this region more susceptible to lightning. Moreover, hilltops often serve as natural lightning attractors. Fig. 3 presents the state spatial distribution of the Lightning Flashes (C-G) for the studied period, *i.e.*, 2019-2023. The geographical diversity, encompassing hills, plateaus, and forests, creates an environment conducive to thunderstorms and lightning strikes. In response, the state government has implemented measures such as early warning systems, lightning protection arresters, and shelters to mitigate the impact on its population and infrastructure.

2.2. *Data source*

This study uses three sets of datasets: LLN-based sensor data for geo referenced lightning strikes, associated lightning district-wise causality data for the studied period, and SRTM elevation datasets. Table 1 outlines the details.

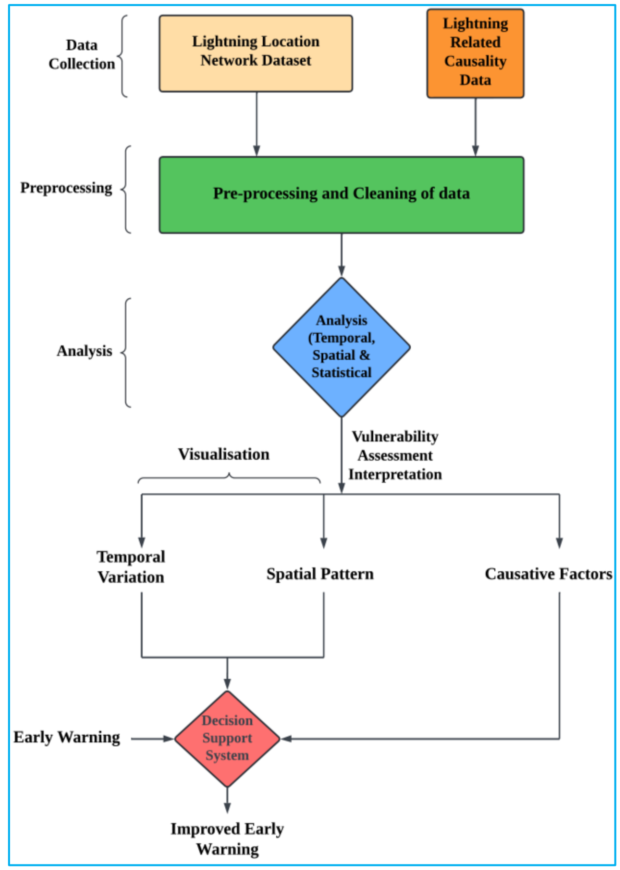


Fig. 4. Outlines a structured approach to analyzing lightning strike data in Jharkhand

2.2.1. *Sensor data*

In 2018, IITM Pune established the LLN to cover the geographical area of Jharkhand. Earth Networks Ltd. manufactures lightning sensors for this network, designed to detect and accurately locate lightning strikes within a 300-meter range (Bui *et al.*, 2016). The sensors employed by LLN are highly efficient, with a detection capability of 90% for C-G lightning strikes in the frequency range of 1 kHz to 1 MHz. They also detect I-C lightning in the frequency range of 1-12 MHz with an efficiency of 85% (Mudiar *et al.*, 2021). The LLN data includes both C-G and I-C lightning strikes. The polarity of the discharge further classifies C-G lightning strikes into negative and positive types. Negative C-G strikes are more common and typically originate from the lower portions of thunderclouds, while positive C-G strikes originate from the upper portions and are often more intense. IITM Pune ensures quality control of the LLN data for the study period (Ghosh *et al.*, 2023). This quality control process aims to validate the accuracy and reliability of the lightning strike data collected by the sensors. The comprehensive coverage provided by LLN

TABLE 2

Year-wise total count of flashes (IC, CG, NCG and PCG) over Jharkhand state

Year	Counts of IC	Counts of CG	Counts of NCG	Counts of PCG
2019	419469	321579	268236	53343
2020	353620	235023	194354	40669
2021	495249	433808	371407	62401
2022	606755	428909	371323	57586
2023	403223	322310	274867	47443

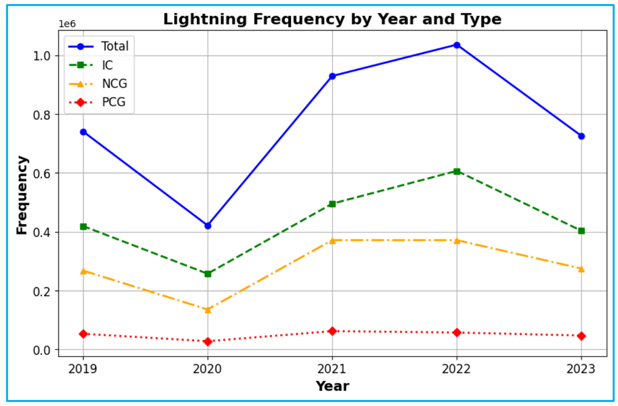


Fig. 5. Annual Lightning Flashes (Total, IC, NCG and PCG) over the State of Jharkhand, India, from 2019 to 2023

allows for detailed analysis and mapping of lightning activity across Jharkhand, contributing to a better understanding and mitigation of lightning-related risks in the region. Table 2 presents the yearly total flashes of IC, CG, NCG and PCG across the state of Jharkhand.

2.2.2. *Lightning-related casualties*

Lightning fatality data spanning from 2018-19 to 2022-23 was gathered from the Department of Home, Jail, and Disaster Management, Government of Jharkhand. This data, used for ex-gratia payments to victims, underwent rigorous quality control measures. However, the data compilation for media reports for the most recent year, 2023-24, may have resulted in underreporting (Shankar *et al.*, 2024). It's important to note that the current dataset doesn't allow for specific instances where multiple fatalities occurred due to the same lightning event. Mortality rates across all districts of Jharkhand from 2018-19 to 2023-24 were calculated and assessed. These mortality data were visualized using QGIS software to depict the variations among districts.

3. Methodology

The methodology outlines a structured approach to analyzing lightning strike data algorithm-associated casualty data in Jharkhand, covering data collection, pre-processing, temporal analysis, spatial analysis, statistical analysis, visualization, interpretation, causative factors, *etc.* Fig. 4 presents the detailed steps of the methodology. In the pre-processing of the data, every lightning flash is analyzed by putting unprocessed data into a Microsoft Excel spreadsheet and arranging it based on the Universal Time Coordinate (UTC) time. Thereafter, the raw data was processed and organized by hour, month, season and various years. Python libraries were used to create different combinations of analysis graphs. To generate thematic maps that illustrate spatial and temporal variations, the study employed district and physiographic division point locations as inputs in Python. Morality data was visualized using QGIS@3.14.

3.1. *Spatio-Temporal Analysis*

The study utilized the kernel density approach to analyze the intensity and spatial pattern of lightning activity. This method entails overlaying a sleek surface onto each geographical point characteristic and calculating the density of lightning strikes about those spots. The density is calculated by aggregating the values of various kernel surfaces within a defined radius or bandwidth (h), with higher values near the reference point feature decreasing as distance increases (Anderson, 2009; Mala and Jat, 2019; Mishra *et al.*, 2023). The following equation (1) serves as the foundation for the formulation of kernel density estimation (Silverman, 2018).

$$\widehat{f(x)} = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - X_i}{h}\right) \quad (1)$$

Kernel density is a mathematical function that calculates the density of a set of data points. It is defined as the sum of a kernel function applied to each data point, where the kernel function measures the distance between a given point and the data points. Typically, the symbol K represents the kernel function, while $x - X_i$ denotes the distance between two points. The parameter h is used to represent the kernel function's bandwidth.

$$Kernal\ Density = \frac{nh}{d} \quad (2)$$

The expression calculates the sum of the kernel function K, evaluated at the Euclidean distance between each point *i* and the geographical location *x*, multiplied by the band width *h*. The number of points inside the radius

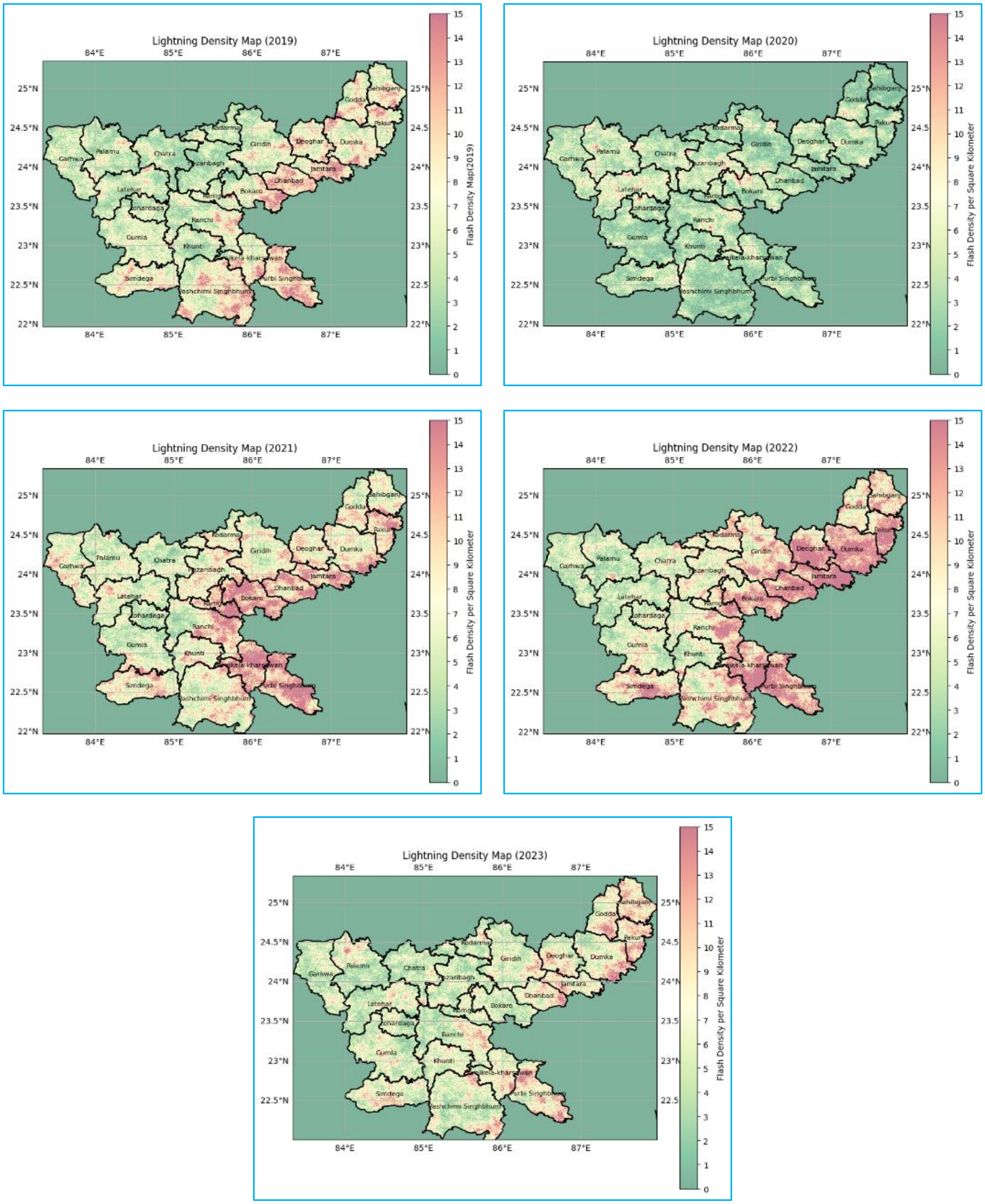


Fig. 6. Shows the yearly spatial distribution of total lightning flash density over the state of Jharkhand from 2019 to 2023

is denoted by *n* and the dimensionality is denoted by *d*. Maps depicting the density of lightning flashes per square kilometer (LFD = flash/km^2) were created for the state of Jharkhand. The classifications of lightning intensity observed ranged from less than 1 flash per square kilometer to more than 60 flashes per square kilometer, offering valuable information about the spatial distribution of lightning intensity throughout the state.(Attri and Tyagi, 2010) Proposed a classification that identified four distinct seasons: winter (January-February), pre-monsoon (March-May), monsoon (June-September), and post-monsoon (October–December) to investigate the fluctuations in lightning activity throughout the year in the state of Jharkhand. Significantly, the study did not include climatology data to assess long-term patterns but rather concentrated on examining the geographical and temporal behavior of lightning within specific periods.

4. Results and analysis

4.1. *Spatio-temporal Patterns of Lightning*

The spatial and temporal patterns of lightning activity can shed light on Jharkhand's vulnerability to this natural disaster. This study investigated the occurrence and distribution of lightning strikes to find areas with a high frequency of strikes and determine any patterns that occur during specific months and seasons. These findings are necessary for developing focused mitigation strategies, increasing public awareness, and enhancing the lightning resilience of infrastructure systems. Fig. 5. displays the statistical data on different types of lightning flashes (IC, CG, PCG and NCG) occurring in the state of Jharkhand from 2019 to 2023. The investigation found an average of 770,572 flashes, with notable fluctuations over the years. The frequency of flash incidents reached its peak in 2022 but declined in 2020. Throughout the research, there were an average of 284,369 NCG strikes and 49,768 PCG strikes taking place across the state. This study improves comprehension of lightning dynamics and is crucial for formulating safety measures and emergency protocols for occurrences of lightning in the state of Jharkhand.

4.2. *Annual Spatiotemporal Lightning Flash Density*

Annually, it is critical to analyze the lightning flash density (LFD) to gain insights into the spatial distribution and frequency of lightning strikes within a specific region. This statistic is utilized to quantify lightning activity, pinpoint high-risk areas, and develop efficient remedies. Regional risk assessments can be enhanced by analyzing atmospheric conditions and gathering pertinent insights. Research of this nature also contributes to the advancement of public awareness campaigns, the deployment of lightning detectors and arrestors, and mitigation techniques. Focusing on the yearly frequency of lightning flashes intensifies the spatial and temporal patterns of lightning events. Fig. 6. shows the total density of lightning flashes in Jharkhand between 2019 and 2023. The research indicates that the eastern edge of the state, as well as some areas in the southwest (specifically the districts of Simdega) and northwest (specifically the districts of Palamu), experience the most frequent occurrences of lightning flashes. These areas are characterized by changes in the topography. Although most of the research region has modest levels of LFD, there are a few locations that show quite high levels. To enhance urban and rural resilience and public safety, it is essential to have a comprehensive understanding of the dynamics of lightning activity in the state of Jharkhand. This study conducted a comprehensive examination of many characteristics related to lightning events, including their distribution, intensity and frequency. The descriptive data does not exhibit any noticeable pattern, indicating that the LFD values were constant throughout the research period. The concentration of lightning was higher at the eastern edge of the state, primarily due to the increasing occurrence of nor'westers. On the other hand, western disturbances primarily trigger lightning in the north-western region, whereas intense monsoonal activity in the south-western region and southern Jharkhand stems from depression, cyclonic storms, and other factors.

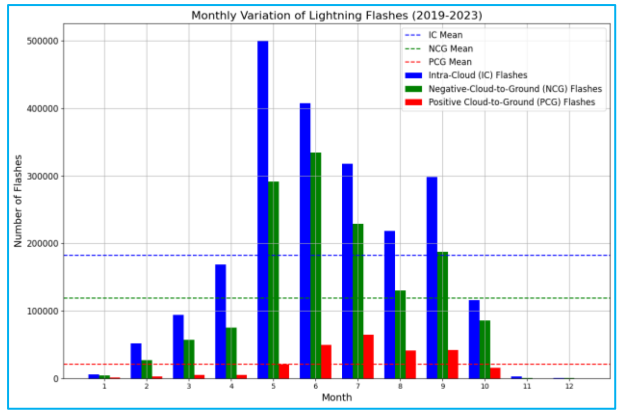


Fig. 7. Monthly variation of lightning flash density (IC, NCG and PCG) over the state of Jharkhand, India

4.3. *Monthly Lightning Flash Density*

Fig. 7 illustrates the monthly distribution of lightning flash rates, specifically for IC, NCG and PCG flashes. May, June, and September had the highest annual IC flash rates. It is worth mentioning that May and June had the highest occurrences of NCG lightning and the maximum number of PCG flashes compared to July. The frequency of lightning flashes for all categories (IC, NCG and PCG) reached their minimum values during the period from November to February. Since April, there has been a discernible increase in lightning activity, coinciding with the onset of thunderstorm activity and the feeding of moisture from the Bay of Bengal. The highest rate of

Monthly flash density maps within Jharkhand districts

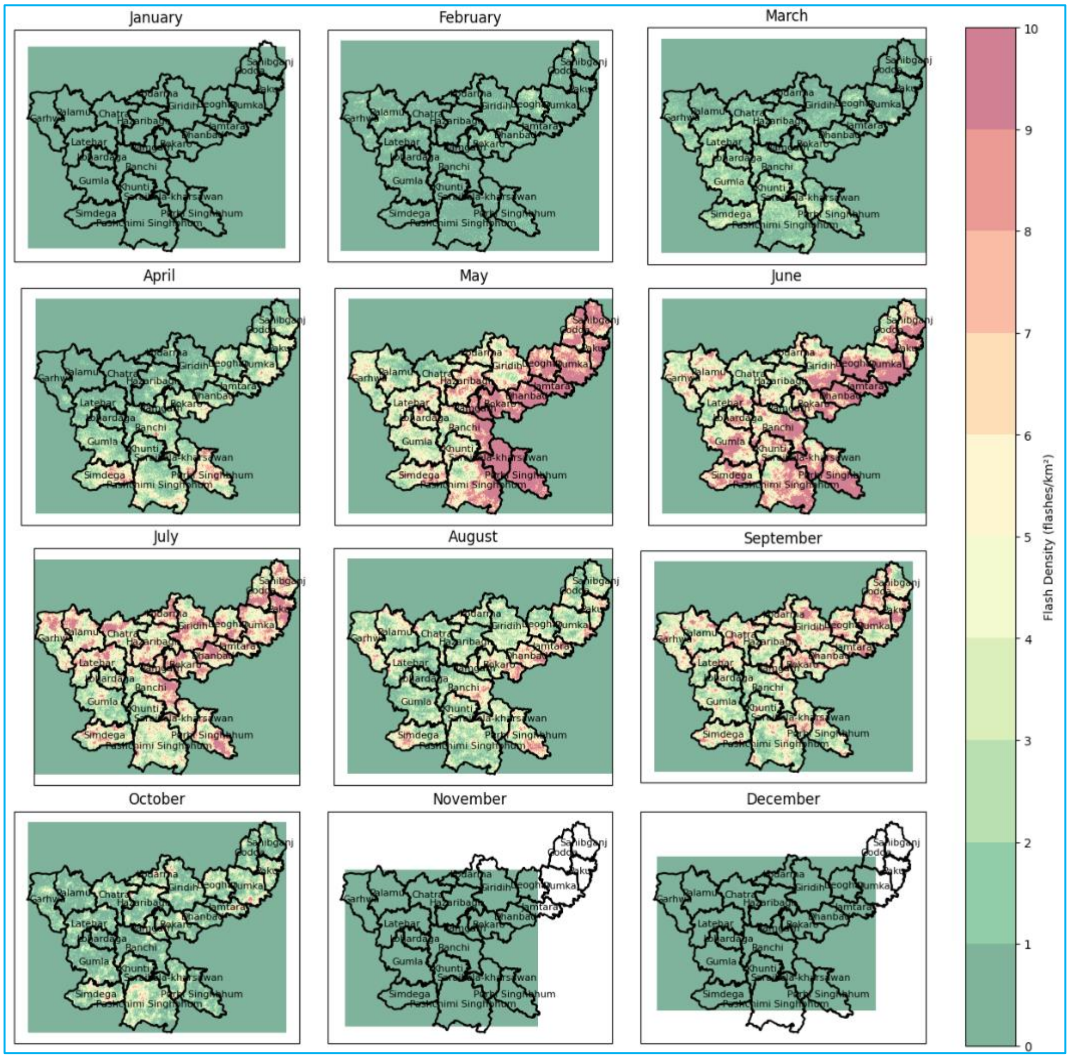


Fig. 8. Monthly spatial variation of CG lightning flash density over the state of Jharkhand, India

lightning occurs in September, coinciding with the formation of a low, a depression in the Bay of Bengal, climatological movements over the state and the monsoon's retreat.

Fig. 8. presents the monthly spatial distribution of C-G lightning. In January and February, the spatial distribution of lightning flash density is negligible and shows no trend. This is attributed to the low temperatures of the winter season. Strong western disturbances in central and eastern India may induce isolated incidents in Deoghar and Bokaro, causing slight moisture incursions from the Bay of Bengal. In March, there were some hotspots of low lightning flash density in the southern part of the state, including the districts of Simdega, Saraikela Kharsawan, and Purbi Singhbhum, as well as in some parts of central Jharkhand. This is likely due to the beginning of the pre-monsoon season when temperatures start rising and a trough or wind discontinuity from Gangetic West Bengal to Vidharbha at low levels gives rise to thunder in the south and central parts of Jharkhand. The eastern, southern, and adjoining central districts of Jharkhand observe marked hotspots of moderate lightning flash density in April. Rising temperatures, a trough in the north-south westerly winds, and continued moisture flow from an anticyclone over the Bay of Bengal are responsible for the increase in flash density compared to March. The interaction between westerly winds in the upper levels and easterly winds in the lower levels can sometimes cause instability in the atmosphere. The eastern part and adjoining southern and central parts of the state predominantly witness clear hotspots with the highest

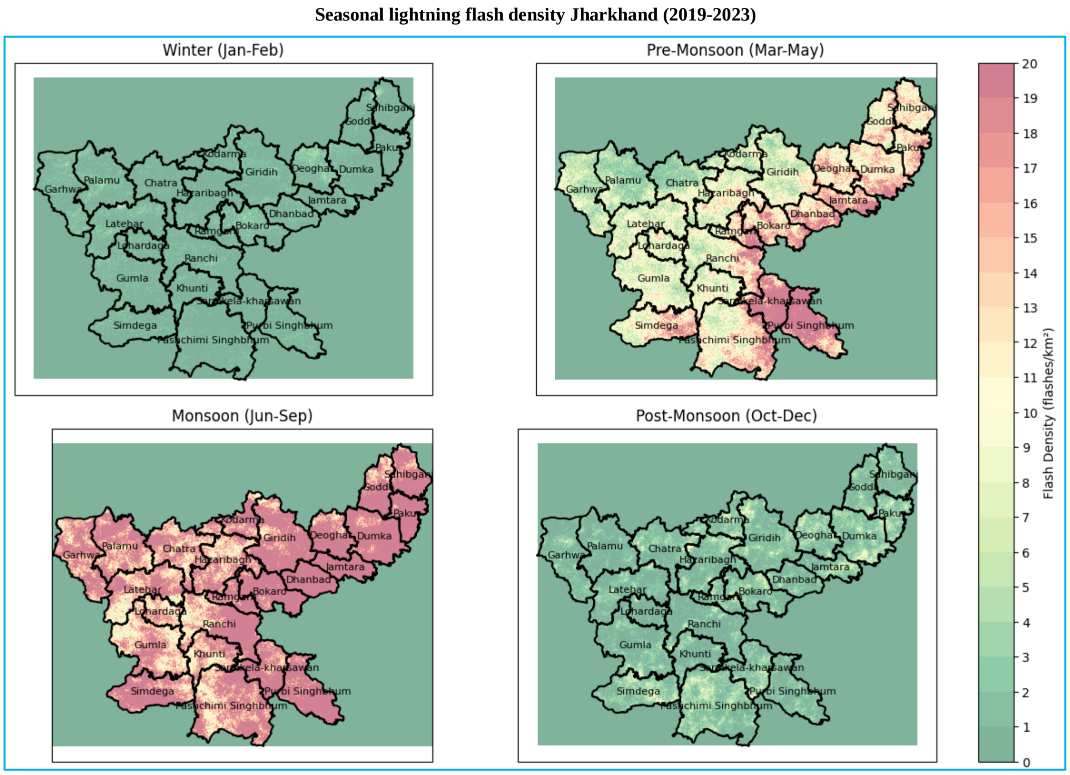


Fig. 9. Seasonal Spatial Patterns of C-G Lightning Flash Density (LFD)

lightning flash density in May. The districts of Jamtara, Deoghar, Dumka, Pakur, Godda, Sahebganj, Chatra, Hazaribagh, Koderma, Giridih, Ramgarh, Bokaro, Dhanbad, West Singhbhum, Saraikela-Kharsawan and East Singhbhum experience the highest flash densities. The rest of the state has a light-to-moderate flash density. May has the warmest temperatures of the pre-monsoon season. A high-pressure area at the surface in central India and an anticyclone over the Bay of Bengal control the flow of moisture, as well as a seasonal windbreak or trough and changes in wind speed due to differences in elevation. The troposphere's thermal structure, with warm air advection in the lower levels and cold air advection in the middle levels, increases the lapse rate, leading to increased instability and intense convective activity. Moreover, southerly/south-westerly wind from the Bay of Bengal at lower levels also led to light to moderate rain, accompanied by lightning and gusty wind (Shankar *et al.*, 2022). The cyclonic storm in the North Bay of Bengal, partially impacted by the depression and low pressure that moved to Jharkhand and its adjacent areas, also contributed to moderate to intense thunderstorms in the eastern, adjoining, south, and central parts of Jharkhand.

Similar to May, in June, the eastern part of the state, including the districts of Sahebganj, Pakur, Godda, Deoghar and Dumka Jamtara, as well as the districts of the North Chotanagpur plateau, such as Chatra, Hazaribagh, Koderma, Giridih, Ramgarh, Bokaro, and Dhanbad, and the South Jharkhand districts of West Singhbhum, Saraikela-Kharsawan, and East Singhbhum, exhibit the highest lightning flash density. Additionally, hotspots increased in the southwest and adjoining central parts of the state, including Simdega, Khunti, Gumla, Ranchi, and Lohardaga. Before the start of the monsoon until mid-June, mostly premonsoon thunder activity happens due to the high day temperatures, increased south-westerly winds in the southern part, and interaction with northwesterly winds in the mid-troposphere level. Additionally, monsoon lows and depressions in the head bay of the Bay of Bengal trigger a premonsoon shower before the monsoon onset, leading to intense convection during the monsoon's onset and coverage over Jharkhand. In July, hotspots of moderate to intense lightning flash density are clearly seen in the northern and central parts of the state, including the districts of Sahebganj, Pakur, Godda, Deoghar, Dumka Jamtara, Chatra, Hazaribagh, Koderma, Giridih, Dhanbad, Ranchi, and East Singhbhum. Simdega also gets moderate to intense lightning flash density, as most of the low pressure and depression moving from the Bay of Bengal to Jharkhand will have convergence thereabout. During this month, the monsoon covers the entire state, with mostly southeasterly winds. Rainfall leads to a decrease in temperature and flash density intensity. Monsoon systems often move northwest, shifting the hotspots to the northern and central parts. High convection and convective instability lead to intense thunder when the monsoon resumes from the active break phase. In August, low to moderate flash density is observed across the state. However, hotspots of moderate flash density are seen in the districts of Jamtara, Dhanbad, Bokaro, Ranchi and East Singhbhum due to sufficient moisture incursion from monsoonal activity and convective instability. Simdega also gets moderate to intense lightning flash density, as most of the low pressure and depression moving from the Bay of Bengal to Jharkhand will have convergence thereabout. The monsoon's active break phase also contributes to thunder and lightning activity in August. In September, hotspots of moderate flash density are observed over the northern eastern and northern parts of the state, including the districts of Sahebganj, Pakur, Godda, Deoghar, Dumk, Jamtara Chatra, Hazaribagh, Koderma, Giridih, and Dhanbad. Monsoon rainfall starts to decrease, and temperatures begin to rise, leading to moderate thunderstorms and flash density. The monsoon's active break phase also contributes to the thunder and lightning activity in September.

The north-eastern part of the state, which includes the districts of Jamtara, Deoghar, Dumka, Pakur, Godda, Sahebganj, Chatra, Hazaribagh, Koderma, Giridih, and Dhanbad, experiences hotspots with light to moderate flash density in October. This is due to the retreating monsoon, which generates moderate thunderstorms. Additionally, low-pressure systems or depressions that move from the Bay of Bengal to Jharkhand up to mid-October also contribute to light to moderate thunderstorm activity. In November and December, lightning flash density is negligible, and no hotspots are observed over the state. This can be attributed to low temperatures and a stable atmosphere.

4.4. *Seasonal variations of lightning*

The spatial variations of the seasonal spatial plots of CG Lightning are depicted in Fig. 9. In the northern regions of Jharkhand, particularly in the districts of Palamu, Latehar, Deoghar, Bokaro and Sahibganj, several isolated pockets of lightning hotspots were observed. During the winter season, as illustrated in Fig. 9, the lightning flash density (LFD) was relatively low, ranging from 0 to 3 flashes/km^2. Despite the low overall LFD, Deoghar and Bokaro districts reported the highest lightning activity within these isolated hotspots. Several meteorological factors contribute to the observed lightning activity during the winter. Winter in Jharkhand and surrounding regions is typically associated with stable atmospheric conditions, which generally result in lower thunderstorm and lightning activity compared to other seasons. However, localized convective activities can still occur, often triggered by the passage of western disturbances, which are weather systems originating from the Mediterranean region that brings moisture and instability to the area. These disturbances can lead to sporadic thunderstorm development, even in the relatively cooler winter months. Additionally, topographical features play a significant role in the distribution of lightning activity. The varied terrain in Jharkhand, including its hills and plateaus, can influence local weather patterns and create conditions favorable for lightning in certain pockets. While the overall lightning activity in Jharkhand during winter is low, specific regions experience higher concentrations of lightning due to a combination of local convective activities influenced by topography and occasional western disturbances. These factors contribute to the formation of lightning hotspots in Jharkhand's northern districts. The eastern and southern districts of Jharkhand, particularly East Singhbhum and Kharsawan, exhibit the highest LFD in the pre-monsoon season due to their high susceptibility to lightning activity. Additionally, districts neighboring West Bengal-namely Sahibganj, Pakur, Jamtara, Dhanbad, Bokaro, the eastern parts of Ramgarh and Ranchi-along with Kharsawan, are particularly vulnerable to frequent lightning strikes. Some pockets within the districts of Simdega and Paschim Singhbhum also experience high lightning flash density during this season. The high lightning density in these districts is primarily due to changes in the topography's gradient. The topographical variation, with a mix of plains, plateaus, and hills, significantly influences local weather patterns. In the pre-monsoon season, the increasing temperatures and differential heating of the land surface enhance atmospheric instability. Convective thunderstorms, often accompanied by intense lightning activity, develop as a result of the instability and moisture-laden winds from the Bay of Bengal.

The eastern and southern districts, such as East Singhbhum and Kharsawan, are particularly susceptible due to their specific topographical features. The region's rugged terrain with significant elevation changes promotes the rise of warm, moist air, which cools and condenses to form thunderstorms. Similarly, the neighboring districts of West Bengal, including Sahibganj, Pakur, Jamtara, Dhanbad and others, share similar climatic and topographical conditions, making them prone to high lightning activity. Moreover, the pre-monsoon season is characterized by the convergence of winds from different directions, which further enhances the likelihood of thunderstorm formation. The influx of humid air from the southeast, interacting with the dry and hot air masses over

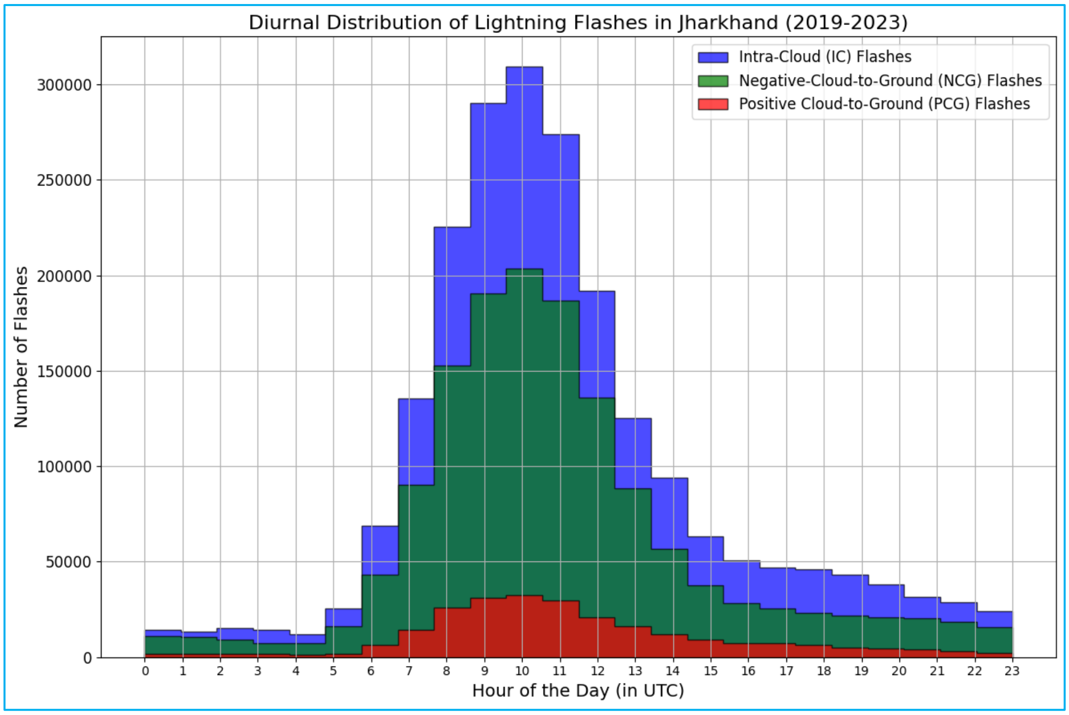


Fig. 10. Diurnal Variations of Lightning Flashes (IC, NCG and PCG) over the State of Jharkhand, India

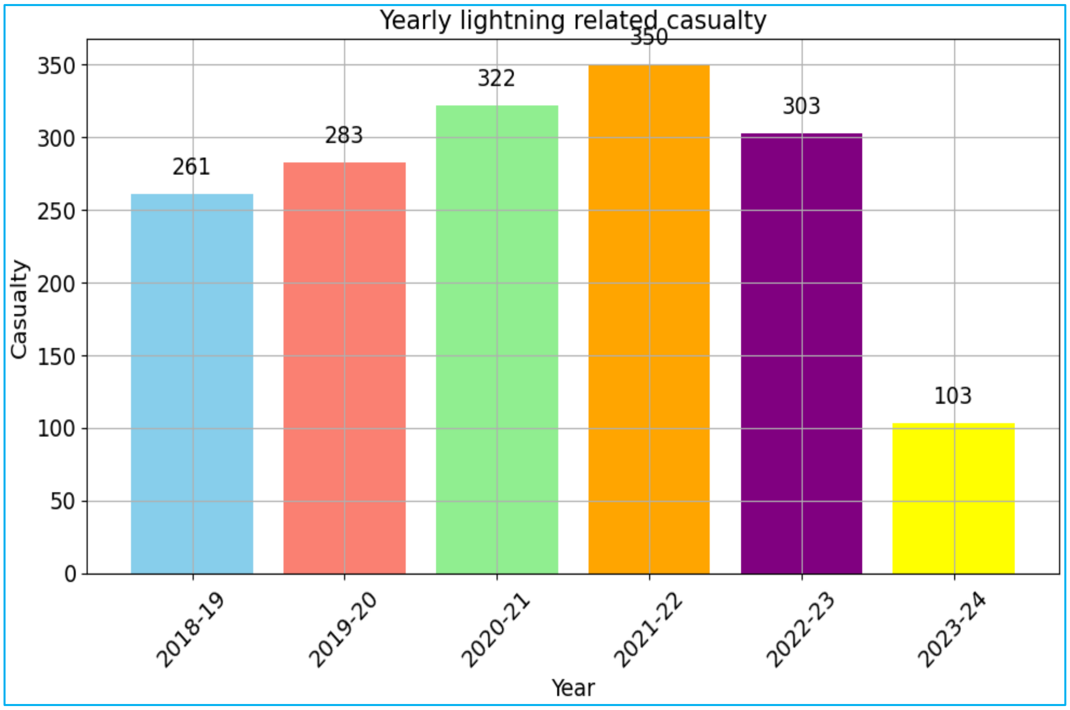
the region, creates an environment conducive to frequent and intense lightning storms. In summary, the high lightning flash density in Jharkhand's eastern and southern districts during the pre-monsoon season is largely due to the combined effects of topographical variation, atmospheric instability, and the interaction of moist and dry air masses. These factors contribute to the formation of convective thunderstorms, resulting in frequent and intense lightning activity in these regions.

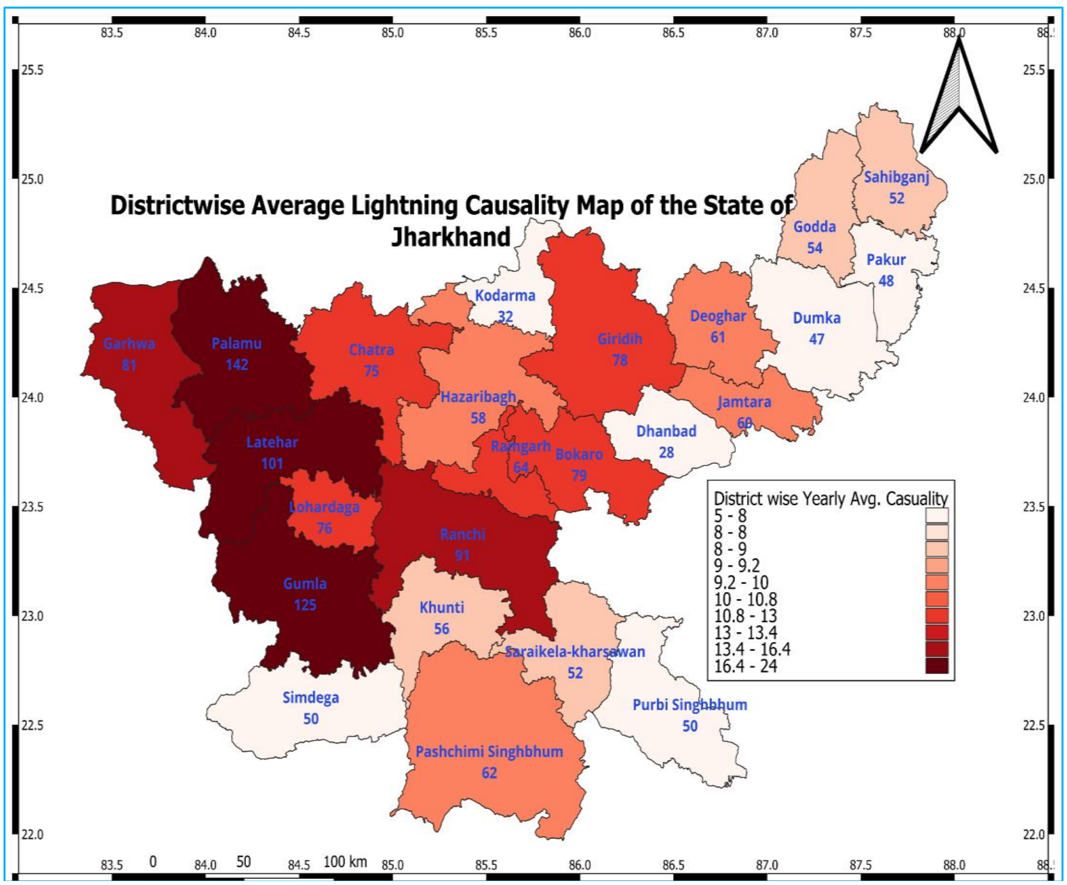
4.5. *Diurnal Variation of Lightning Flash Density*

The diurnal variation of lightning flashes over Jharkhand exhibited a distinct pattern (presented in Fig. 10). Analysis of the data reveals that all three types of lightning-intra-cloud (IC), negative cloud-to-ground (NCG), and positive cloud-to-ground (PCG)-show prominent peaks, with the highest maximum occurring at 1000 UTC. Fig. 10 illustrates the average lightning flash counts, highlighting that lightning activity is most frequent in the late afternoon to early evening, specifically between 0800 UTC and 1300 UTC. This diurnal pattern can be attributed to the daily heating cycle, which influences atmospheric instability and convection processes. As the sun heats the surface throughout the day, the temperature difference between the ground and the upper atmosphere increases, leading to stronger updrafts and the formation of cumulonimbus clouds, which are conducive to lightning. The peak at 1000 UTC corresponds to the late afternoon in local time (approximately 3:30 PM IST), a period typically associated with maximum convective activity due to the accumulated heat. The subsequent decline in lightning activity after 1300 UTC (around 6:30 PM IST) can be linked to the cooling of the surface as the sun sets, reducing the thermal contrast and, consequently, the convective strength needed to sustain thunderstorm development. This pattern of diurnal variation is consistent with the typical behavior of thunderstorms in tropical and subtropical regions, where the interplay between solar heating and atmospheric dynamics governs the timing and intensity of lightning activity.

4.6. *Spatial and temporal distribution of lightning-related casualties*

The Department of Home, Jail, and Disaster Management, Government of Jharkhand, has provided a restricted collection of statistics regarding deaths caused by lightning in the state from the years 2018-19 to 2022-23. However, data for the years 2023-24 was collected from newspapers and electronic media, indicating a potential for underreporting during this period. Between 2018-19 and 2023-24, there were a total of 1622 deaths reported in different districts of Jharkhand. The districts with the highest number of fatalities were Palamu (142),





Figs. 11(a&b). Lightning fatalities in Jharkhand. (a) The plot depicting the time series; (b) The spatial plot representing the district-wise fatalities

Latehar (125) and Gumla (101). Lightning activity causes an average of 270 fatalities every year. Fig. 10(a) depicts the time series distribution of deaths caused by lightning. In the years 2021-22, high cases of lightning-related fatalities may be owing to the active pre-monsoon and monsoon seasons. Fig. 10(b) depicts a spatial distribution of lightning-related fatalities categorized by district. The districts of Palamu, Garwa and Lathar experienced the highest number of lightning-related fatalities. This may be attributed to their larger areas, high topography and agriculture-intensive regions, which contrast with the more urbanized and industrialized eastern and southern parts of the state. The updrafts and downdrafts associated with thunderstorms over hilly terrain generate strong electrical charges, making this region more susceptible to lightning. Moreover, hilltops often serve as natural lightning attractors.

4.7. *Factors Influencing the Occurrence of Lightning Activity*

Multiple factors influence lightning strikes in Jharkhand, which are linked to geographic, meteorological and environmental traits.

4.7.1. *Geographical factors*

Topography: Jharkhand's rugged hills, plateaus, and dense forests significantly contribute to the high incidence of lightning strikes. The updrafts and downdrafts associated with thunderstorms over hilly terrain generate strong electrical charges, making this region more susceptible to lightning. Moreover, hilltops often serve as natural lightning attractors.

Geographical distribution: Jharkhand's districts have an uneven distribution of lightning-related fatalities. Districts like Garhwa, Palamu and Latehar, characterized by hilly terrain and frequent lightning activity, report higher numbers of lightning-related deaths. This uneven distribution underscores varying levels of thunderstorm intensity across different areas.

4.7.2. *Meteorological Factors*

Monsoon Season: From June to September, Jharkhand experiences its peak lightning activity during the monsoon season. Warm and humid conditions prevail, creating an ideal environment for thunderstorms and lightning strikes. Rapidly rising warm air, combined with a moisture influx from the Bay of Bengal, enhances thunderstorm formation.

Solar Heating and Wind Patterns: Pre-monsoon and monsoon months witness the influence of extended troughs and wind discontinuities triggered by solar heating. These atmospheric conditions heighten instability, fostering thunderstorm development and increasing the likelihood of lightning strikes.

4.7.3. *Environmental factors*

Vegetation: The presence of tall trees, particularly in hilly regions, acts as natural lightning conductors. Farmers working in open fields surrounded by tall trees face an elevated risk, as evidenced by the significant number of lightning-related fatalities among agricultural workers.

Aerosol property: The Jharkhand state is a highly industrialized state with a concentration of thermal power plants with a mining industry of coal, iron, mica, and uranium and ancillary industrial units in the eastern and southern parts of the state. Due to this, the aerosol property of that area changes which contributes to the enhancement of severe thunderstorms.

This logically presents the geographical, meteorological, and environmental factors contributing to lightning strikes in Jharkhand, emphasizing their interplay with the region's lightning vulnerability.

4.8. *Challenges and Proposed Solutions for Disseminating Lightning Early Warnings*

In Jharkhand, the mitigation of lightning casualties involves a range of potential measures, including enhancing early warning systems, improving public communication for individual action to reduce exposure and vulnerability, and integrating lightning protection measures. Lightning poses a unique challenge compared to other natural disasters due to its sudden and swift nature, striking within seconds and leaving victims with little time to react. A structured early warning system with forecasts issued by the India Meteorological Department (IMD) could significantly mitigate risks if effectively disseminated to vulnerable populations. While efforts such as the Incident Response System (IRS) exist at state and district levels, there is a notable absence of institutionalized IRS at lower administrative levels like blocks, panchayats, and villages. This gap hinders the effective dissemination of lightning-quick warnings and enforcement of safety standards, exacerbating the risk for vulnerable populations. Awareness among villagers about basic lightning safety norms-such as avoiding standing under trees or in open areas during thunderstorms-is lacking. Mass-scale awareness campaigns led by trained personnel at the panchayat and village levels, including teachers, local leaders and self-help groups, are essential to promoting lightning safety practices. Moreover, housing standards in rural areas of Jharkhand, characterized by tin roofs, exacerbate lightning hazards due to metal's propensity to attract lightning strikes. The absence of proper grounding and lightning protection devices further increases casualties in these regions. Therefore, states should prioritize enhancing their early warning systems, improving public awareness, and implementing robust lightning protection measures to mitigate the devastating impact of lightning hazards across the state.

5. Conclusions

This study provides a comprehensive analysis of lightning activity and its causal association with fatalities in the state of Jharkhand, highlighting significant annual variability and spatial concentrations of lightning strikes. Over the period from 2019 to 2023, an average of 770,572 lightning flashes was recorded annually, with notable fluctuations observed between years. The peak in 2022 indicates the dynamic nature of lightning occurrences in the region, emphasizing the need for ongoing monitoring and mitigation efforts to address varying levels of lightning risk across the state. Spatially, lightning strikes in Jharkhand exhibit distinct patterns, with higher flash densities concentrated along the eastern edge and in specific southwestern districts. These spatial variations underscore the influence of geographical factors such as topography and land use on local lightning vulnerability. Understanding these spatial dynamics is crucial for targeted mitigation strategies and infrastructure resilience planning to minimize the impact of lightning-related hazards on communities. Seasonal analysis reveals pronounced peaks in lightning activity during the pre-monsoon and monsoon periods, typically from May to September. Increased convective instability and a moisture influx from the Bay of Bengal drive this heightened activity, creating favorable conditions for thunderstorm development. May and June stand out as months with the highest lightning densities, aligning with peak atmospheric instability and convective processes during the onset of the pre-monsoon season. Diurnal variations in lightning activity show distinct peaks in the late afternoon, corresponding to maximum solar heating and convective activity. This diurnal pattern highlights the role of daily heating cycles in triggering thunderstorms and subsequent lightning events in Jharkhand. Understanding these temporal patterns is essential for optimizing lightning detection and warning systems to enhance public safety and disaster preparedness measures during peak lightning hours. Factors influencing lightning activity in Jharkhand include geographical features like hills and plateaus, which contribute to enhanced lightning susceptibility, particularly in regions with rugged terrain. Meteorological factors such as monsoon dynamics and wind patterns from the Bay of Bengal play significant roles in seasonal variations of lightning activity. Additionally, environmental factors such as vegetation density influence local lightning risk, which has implications for agricultural and rural communities. The updrafts and downdrafts associated with thunderstorms over hilly terrain generate strong electrical charges, making this region more susceptible to lightning. Moreover, hilltops often serve as natural lightning attractors. This study underscores the importance of understanding spatiotemporal patterns of lightning in Jharkhand for developing effective mitigation strategies and enhancing disaster preparedness. By integrating these findings into local planning and resilience efforts, stakeholders can better safeguard communities against the impacts of lightning-related hazards. Future research directions could focus on refining predictive models and assessing long-term trends to support climate change adaptation and resilience-building initiatives in the region.

Data Availability

The Indian Institute of Tropical Meteorology Pune provided the Lightning Location Network datasets, utilizing lightning detection sensors located both within and around the study areas. The quality-controlled statistics of lightning-related fatalities were obtained from the Department of Home, Jail, and Disaster Management, which is part of the Government of Jharkhand. The SRTM DEM (F) data was accessed from https://earthexplorer.usgs.gov/.

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Conflict of Interest

The authors declare that the research was conducted without a commercial or financial relationship that could be interpreted as a potential conflict of interest.

Authors' Contributions

Abhishek Anand: Conceptualization, Validation.
Anand Shankar: Methodology, Software, Writing Original Draft, Writing Review & Editing.
Ashish Kumar : Supervision.
Surendra Pratap Singh: Supervision.

Disclaimer: The contents and views presented in this research article/paper are the views of the authors and do not necessarily reflect the views of the organizations they belongs to.

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Appendix A. Acronyms

Table A.1 shows a list of alphabetically ordered acronyms that appear in this paper.

TABLE A.1

Acronyms	Full Name
CAPE	Convective Available Potential Energy
CG	Cloud-to-Ground
IC	Intra-Clouds
IITM	Indian Institute of Tropical Meteorology
IMD	India Meteorological Department
IRS	Incident Response System
LFD	Lightning Flash Density
LIS	Lightning Imaging Sensor
LLN	Lightning Location Network
MSLP	Mean Sea Level Pressure
NCG	Negative Cloud-to-Ground
PCG	Positive Cloud-to-Ground
SRTM DEM	Shuttle Radar Topography Mission Digital Elevation Model
TRMM	Tropical Rainfall Measuring Mission
UTC	Universal Time Coordinate