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Spatial Mapping of Lightning Flash Characteristics in Windstorm-Prone Areas

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Abstract: Tropical thunderstorms, characterized by intense convective activity, pose significant risks in equatorial regions like Malaysia, where they often produce severe wind gusts and frequent lightning. The relationship between lightning activity and windstorm dynamics remains underexplored, particularly in tropical mesoscale convective systems (MCS). This research investigates the spatial distribution of lightning flash types, which are cloud flashes (IC), negative cloud-to-ground flashes (-CG), and positive cloud-to-ground flashes (+CG), across radial zones (5 km, 10 km, 15 km) during a windstorm event in Johor Bahru on 30 November 2022. Quantum Geographic Information System (QGIS) software was used to map and analyze the spatial distribution of lightning flashes. IC flashes dominated near the thunderstorm core (15.76% within 5 km), while CG flashes were most prevalent (84.24% within 5 km), indicating strong updrafts and charge separation. In contrast, +CG flashes were rare near the core but increased slightly at greater distances (2.78% at 10 km), suggesting charge redistribution during thunderstorm decay. The findings demonstrate that fine-scale radial zoning of lightning data can improve storm structure analysis and early warning systems in tropical regions.

Keywords: Cloud Flash, Radial zones, Lightning Activity, Thunderstorm, Windstorm

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1. INTRODUCTION

Tropical thunderstorms are a common and significant weather phenomenon in equatorial regions such as Malaysia [1]–[3]. Characterized by warm, moist atmospheric conditions and strong convective activity, these thunderstorms often produce intense rainfall, gusty winds, and frequent lightning activity [4], [5]. Windstorms associated with tropical thunderstorms can cause localized damage, particularly in urban areas where severe gusts and microbursts are more impactful. Convective thunderstorms typically develop rapidly in Malaysia due to daytime heating and moisture convergence, leading to sudden and severe weather events [4], [6].

Lightning analysis plays a vital role in understanding thunderstorms' internal structure and life cycle. The type, frequency, and spatial distribution of lightning flashes can reveal key information about thunderstorm dynamics, such as updraft strength, charge separation mechanisms, and the maturity stage of convective systems. The movement of charged particles by updrafts and gravity leads to the formation of distinct charge centres and electrical structures, such as the basic tripolar configuration, where a main negative charge centre is positioned at mid-levels, with positive charge layers found at both the upper and lower parts of the thunderstorm. Cloud flashes (IC) typically begin between the main negative and upper positive charge regions, whereas cloud-to-ground (CG) flashes generally occur between the main negative charge centre and either a lower positive region or the ground. IC flashes are usually more numerous in most thunderstorms than CG flashes [7].

Shikhov et al. [8] analyzed the severe convective outbreak in Western Siberia from 25–26 May 2020, lightning activity was matched with satellite-observed thunderstorm cores. Most lightning flashes were found within 50 km of the thunderstorm centres, showing strong spatial alignment. A less than 50 km was used because it accounts for the typical scale of thunderstorm core structures and minimizes errors from satellite viewing angles and lightning location accuracy.

Meanwhile, Li et al. [9] highlighted that the tornado occurred approximately 15 km from the main lightning discharge center and near a lightning hole, a region with significantly reduced lightning activity. This finding suggests that tornado formation is not necessarily associated with the areas of highest lightning density but can occur near regions of suppressed lightning activity. By focusing on this distance and the presence of the lightning hole, the study emphasizes the importance of monitoring both high-density and low-density lightning regions for more effective tornado detection and early warning. Additionally, the author observed that IC flashes consistently dominated across all distances within different radial zones from the thunderstorm centre. In contrast, CG flashes were more concentrated near the tornado region, and +CG flashes, although less frequent overall, showed noticeable fluctuations with distance, highlighting distinct spatial patterns of lightning polarity associated with tornadic thunderstorms.

This research addresses that gap by investigating the spatial variation of lightning flash types across radial distance zones during a significant windstorm in Johor Bahru, Malaysia, on 30 November 2022. By dividing the lightning data into 5 km, 10 km, and 15 km zones from the thunderstorm centre, this research provides a detailed understanding of how lightning activity is organized spatially around a tropical convective windstorm. While previous studies demonstrated the importance of distance-based lightning analysis around thunderstorm cores and tornado events, this study further refines the approach by applying smaller radial distances to a tropical severe windstorm, offering more detailed insights into lightning spatial variation at finer scales. This research aims to assess the distribution and variation of IC, -CG, and +CG lightning flashes within different radial zones around the tropical windstorm core.

2. METHODS

This study investigates the spatial distribution of lightning flash types associated with a severe windstorm in Johor Bahru, Malaysia. Lightning data were acquired from Tenaga Nasional Berhad Research (TNBR), which provided detailed records, including flash type, geographic coordinates, and time of occurrence. The lightning data used in this study were collected from a network of five LS7002 sensors installed by TNBR across Peninsular Malaysia.

The sensors are placed up to 350 km apart to cover the entire region, with one sensor located in Kulai, Johor, for the southern area and the others positioned in the central, northern, eastern, and western parts [10], [11]. The LS7002 sensors work in the low-frequency range (30 kHz to 300 kHz), where most lightning signals are strongest, allowing them to detect lightning from long distances. Instead of relying on a single sensor, the system determines the location of lightning flashes by combining data from at least three or four sensors. The sensors use a mix of Time-of-Arrival (TOA) and Magnetic Direction Finding (MDF) methods to locate each lightning activity accurately [12].

Three radial zones were established at distances of 5 km, 10 km, and 15 km from the windstorm centre to systematically examine the lightning activity around the windstorm event. Lightning flashes were categorized based on proximity to the event centre within these concentric zones. Each flash was further classified into three types: IC flashes, -CG flashes, and +CG flashes. This classification allowed for the differentiation of lightning activity associated with different thunderstorm stages and structures.

Quantum Geographic Information System (QGIS) software was used to visualize the spatial distribution of lightning activity. The lightning flash data, including their geographic coordinates, were imported into QGIS and plotted onto a study area map. Circles with radii of 5 km, 10 km, and 15 km were drawn around the centre of the windstorm to mark the three different zones. Each lightning flash was sorted into a zone based on its location within these circles. Different colours and symbols were used to represent each type of lightning, IC, -CG, and +CG, making it easy to see the differences across the zones. High-quality maps were created using these tools (Figures 1, 2, and 3) to show how lightning activity changed with distance from the windstorm centre. QGIS provides a practical and accurate way to organize, analyze, and display the spatial lightning data.

3. RESULTS AND DISCUSSION

3.1 Overview of Lightning Flash Distribution

Figures 1, 2, and 3 illustrate the spatial distribution of lightning flashes within 5 km, 10 km, and 15 km radial zones, respectively, centered around the windstorm event in Johor Bahru. Each figure categorizes lightning types as -CG, +CG, and IC. A total of 512 lightning flashes were recorded during the thunderstorm, with distinct variations in density and type as the distance from the windstorm increased. The spatial clustering of IC flashes near the core and the outward shift in +CG activity align with the conceptual model of charge separation in tropical thunderstorms, where updrafts dominate the inner core while downdrafts and anvil spreading influence outer regions [7].

Table 1 summarizes lightning activity across the three zones. The data reveals a clear trend: IC flashes dominate near the windstorm core, while +CG flashes become more prevalent with distance. Percentages indicate the proportion of each lightning type relative to the total flashes in each zone. This research's spatial pattern of lightning activity aligns with established thunderstorm electrification theories and similar research findings. Notably, the absence of +CG flashes in the 5 km zone contrasts with midlatitude storm studies by Shikhov et al. [8]. Tropical windstorms may exhibit a unique charge distribution due to higher atmospheric energy for convection and moisture content.

Table 1. Number and percentage of lightning types (IC, -CG, +CG) within 5 km, 10 km, and 15 km from the windstorm event in Johor Bahru.

Distance	Total flashes (%)	IC (%)	-CG (%)	+CG (%)
5 km	184 (35.94%)	29(15.76 %)	155(84.24 %)	0(0.00 %)
10 km	180 (35.16%)	45(25.00 %)	130(72.22 %)	5(2.78 %)
15 km	148 (28.91%)	41(27.70 %)	103(69.59%)	4(2.70%)

The dominance of IC flashes near the windstorm core supports the hypothesis that intense convective updrafts drive charge separation in the thunderstorm's core. This is consistent with the study by Li et al. [9], which highlighted that IC flashes predominate during thunderstorms' development and maturation stages. Furthermore, the increase in +CG flashes at greater distances (10 km and 15 km zones) parallels observations suggested that +CG activity signals the transition to dissipating storm stages or interactions at the thunderstorm's outer area.

3.2 Lightning Activity within 5 km zone

The 5 km radius zone exhibited the highest lightning concentration, accounting for 35.94% of total activity. Notably, IC flashes comprised 15.76% of flashes in this zone, while CG flashes dominated at 84.24%. The absence of +CG flashes suggest the thunderstorm was in an early or mature stage, characterized by strong updrafts and active charge separation within the convective core. The high -CG flash density may reflect vigorous negative charge layer formation near the freezing level, as observed in tropical squall lines [4]. The elevated IC activity is particularly significant, reflecting vigorous electrification processes typical of intensifying thunderstorms. This zone likely represents the thunderstorm's most electrically active region, where charge layers are vertically aligned and updrafts are strongest.

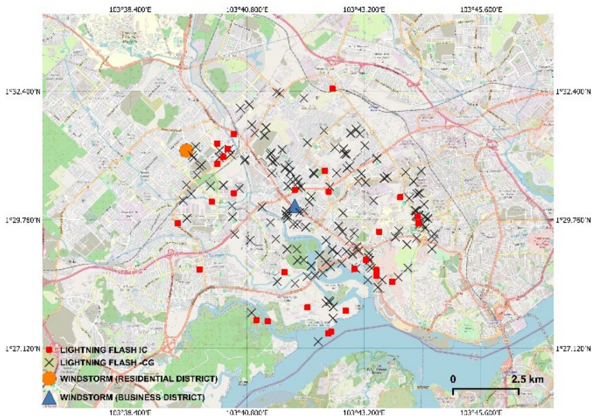

Figure 1. The distance of 5 km from a lightning flash

3.3 Lightning Activity within 10 km zone

The 10 km zone accounted for 35.16% of total lightning activity, with IC flashes increasing to 25.00%. While CG flashes remained dominant (72.22%), the rise in IC activity indicates sustained vertical growth and charge separation at the thunderstorm's outer core. The emergence of +CG flashes (2.78%) suggests initial charge layer tilting or weak updraft interactions, consistent with the "lightning hole" phenomenon observed near tornadic storms by Li et al. [9]. However, the low +CG frequency here implies minimal charge reorganization compared to mid-latitude systems. The presence of +CG flashes suggest localized charge reorganization, possibly due to weakening updrafts or interactions with surrounding air masses. This zone likely marks the transition between the convective core and the thunderstorm's outer region, where charge layers begin to spread horizontally.

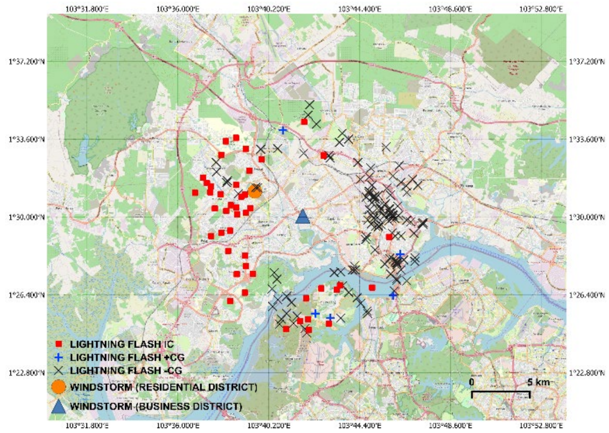

Figure 2. The distance of 10km from a lightning flash

3.4 Lightning Activity within 15 km zone

The 15 km zone showed reduced flash density (28.91% of total activity), with IC flashes peaking at 27.70% relative to other types. The decline in CG flashes (69.59%) and minimal +CG activity (2.70%) suggests the thunderstorm was transitioning to a stratiform structure. The persistent IC flash prevalence at this distance contrasts with temperate thunderstorms, where IC activity typically declines sharply beyond 10 km [5]. This may reflect broader anvil regions in tropical systems due to weaker wind shear. The higher IC proportion implies persistently elevated charge layers, possibly associated with anvil spreading or decaying convection. This zone reflects the thunderstorm's dissipating stage, where updrafts weaken, but residual electrification persists.

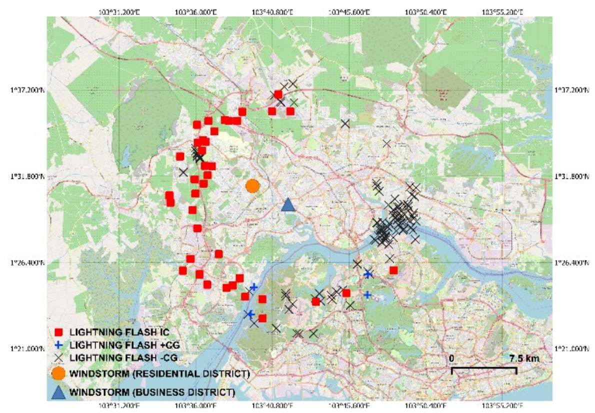

Figure 3. The distance of 15km from the lightning flash

The analysis of lightning flash distribution across radial distance zones of 5 km, 10 km, and 15 km from the thunderstorm centre provides essential insight into the spatial organization of electrical activity within a convective system. This zoning allows for identifying lightning concentration patterns and their variation relative to thunderstorm structure. Typically, higher flash densities, especially of IC lightning, are observed within the innermost 5 km zone, corresponding to the thunderstorm's convective core, where updrafts are most intense. As the distance increases to 10 km and 15 km, the lightning flash rate generally decreases, with a shift in the dominant lightning type, reflecting the thunderstorm system's spatial expansion and structural evolution. This radial approach enhances the understanding of how lightning characteristics are distributed around a thunderstorm and contributes to the broader interpretation of thunderstorm dynamics in tropical regions.

The distribution patterns observed in this research align with established thunderstorm electrification theories, where intense convective cores produce IC lightning at high frequencies, and mature/dissipating storms generate +CG flashes at the edges due to elevated charge layers. From a practical standpoint, this research highlights the importance of monitoring lightning activity in thunderstorm centres and across radial zones. This can improve hazard early warning systems, particularly for +CG flashes that occur far from the main cloud mass and are more likely to cause damage or pose a safety risk. This radial lightning analysis method can also support storm structure interpretation and serve as an early warning tool alongside radar data, especially in tropical regions like Johor Bahru.

This research acknowledges the limitation associated with the analysis of a single severe windstorm event. Nevertheless, it provides meaningful novelty through the introduction of a fine-scale 5 km radial zoning framework, which offers substantially higher spatial resolution than the wide-radius approaches commonly adopted in lightning research. Importantly, the analysis extends beyond descriptive statistics by explicitly relating the spatial distributions of IC, −CG, and +CG flashes to established thunderstorm electrification processes and thunderstorm life-cycle evolution, enabling clear physical interpretation of the observed patterns. In addition, the findings demonstrate practical relevance by highlighting the potential of high-resolution lightning zoning to support tropical storm structure assessment and enhance early warning capabilities. Although validation using multiple events is recommended as future work, the present results constitute a substantive and relevant contribution to the understanding of lightning–windstorm relationships in tropical environments.

4. CONCLUSION

This research demonstrates that lightning distribution varies systematically with radial distance from a thunderstorm's core, revealing distinct spatial patterns where IC and -CG flashes dominate within 5 km, indicating strong updrafts and charge separation, while +CG flashes emerge at 10-15 km, suggesting charge reorganization during storm decay. These findings align with established electrification theories and validate the effectiveness of fine-scale radial zoning (5 km intervals) for analyzing tropical thunderstorms, contrasting with conventional 50 km thresholds. The results provide actionable insights for improving nowcasting systems, particularly in tropical regions, using inner-zone IC flash density as an updraft intensity indicator and outer-zone +CG activity as a dissipation marker. Future research should focus on integrating lightning zoning with radar data to refine the charge structure, ultimately advancing severe weather preparedness in vulnerable equatorial areas.

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