# Analysis of Diurnal and Seasonal Variation of Lightning Activities over Sri Lanka's Maritime Zones

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## 1. ABSTRACT

This study provides an analysis of diurnal variation patterns of lightning activities over Sri Lanka's Maritime Zones; Territorial Sea (T), Contiguous Zone (C) and Exclusive Economic Zone (E), during different climate seasons. For this study, 17 years of lighting data were obtained from the Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measuring Mission (TRMM) satellite from 1998 to 2014. During the first inter-monsoon season (March to April), the diurnal cycle of the lightning over all maritime regions peaked distinctly in the evening, with a maximum at 19:00- 20:00 Local Time (LT). In contrast, minimum lightning activities were recorded during the morning hours. During the southwest monsoon (May to September), a late evening maximum of the diurnal lightning cycle was recorded over the Contiguous zone (20:00-21:00 LT) and the Exclusive economic zone (21:00-22:00 LT), whereas the Territorial Sea is characterized by a pronounced early morning peak at 03:00-04:00 LT. Furthermore, a consistent minimum in activity is evident across all domains during the noon hours. Lightning activity during the second inter-monsoon (October to November), over the Territorial Sea and Contiguous Zone exhibited an evening maximum (20:00-21:00 LT and 19:00-20:00 LT, respectively), the Exclusive Economic Zone is characterized by a pronounced early morning peak at 01:00-02:00 LT. Diurnal variation of lightning activities in the northeast monsoon (December to February) shows that the Territorial Sea and Contiguous Zone experienced an evening maximum (peaking at 19:00-20:00 LT and 18:00-19:00 LT, respectively) and a morning minimum. Conversely, lightning activity over the Exclusive Economic Zone exhibited an early morning peak (04:00-05:00 LT) and its minimum around midday. The cross-correlation shows lightning activities in maritime zones T and C act as strong short-term factors of C and E, with T often leading C and C influencing E, whereas E exhibits weaker or inconsistent associations and no evidence of reverse causality. These findings are specifically important to figure out the lightning peak and minimum time periods over different maritime zones, providing a scientific basis for risk mitigation and vital for the fishing industry to optimize the strategic timing of operations and to mitigate risks associated with lightning-related hazards.

**Keywords:** Lightning, Lightning Hazard, Lightning Disasters, Maritime Zone, LIS, TRMM,

## 2. INTRODUCTION

Lightning has major impacts on the world, causing 6,000 and 24,000 fatalities annually worldwide [1], starting wildfires, damaging infrastructure, altering atmospheric chemistry, and influencing ecosystems and climate processes.

Understanding of lightning distribution over the maritime zones of Sri Lanka is important because oceanic lightning is closely linked to deep convection, severe weather systems, and regional climate variability that affect both marine and coastal environments [2,3,4,5]. On the other hand, lightning over the ocean also contributes to atmospheric chemistry by producing nitrogen oxides and oxidants, influencing ozone formation and air-sea chemical interactions [6]. Satellite-based lightning observations are used in this study because they provide uniform, long-term, and spatially continuous coverage over maritime zones where ground-based lightning detection networks are sparse or absent [7,8].

Due to the strategic location of Sri Lanka in the Indian Ocean, the surrounding maritime area is critically important for the country, making it a key player in global trade, regional security, and economic development. On the other hand, the fishing industry of the country is one of the major sources of income, contributing significantly to Sri Lanka's Gross Domestic Product. Furthermore, the fishing industry provides direct and indirect employment for millions of people in the country. Lightning disasters can harm property and interrupt livelihoods in the agricultural, fishing, and maritime industries. Those damages reduce productivity and economic efficiency by interfering with transportation, industrial output, and essential services. Therefore, understanding atmospheric processes over Sri Lanka's maritime zones is essential for improving weather forecasting, disaster management, and sustainable management of marine and coastal resources. The current study focuses on lightning activities over the maritime zones of the country, where direct observations are limited but lightning poses significant risks to offshore operations, coastal communities, and marine transportation [2,3].

High convection and frequent thunderstorms occur regularly in Sri Lanka, a tropical nation, which increases the frequency of lightning and contributes to these effects. An analogous study shows that average lightning flash density in Sri Lanka is 8.26 flashes $km^{-2}$ $year^{-1}$ [9]. It is a major risk to human safety, leading to fatalities and injuries, particularly among rural people and outdoor workers, particularly in agriculture and fishing [10, 11]. In this study, Lightning Imaging Sensor (LIS) data on Tropical Rainfall Measurement Mission (TRMM) of NASA is used to analyze the diurnal variability of lightning activities in different seasonal periods. As Sri Lanka is lack of Lightning Location System (LLS) to collect the lightning data, the previous studies have utilized LIS on TRMM data to analyze the lightning trend and distribution over particular areas of the country [9, 12, 13, 14].

## 3. MATERIALS AND METHODS

### 3..1 Study Area

Sri Lanka's maritime zones play a vital role in the country's environmental, economic, and strategic framework due to its island location in the northern Indian Ocean. These zones include the Territorial Sea (12 Nautical Miles ($\approx 22\ km$) from coast), Contiguous Zone (24 Nautical Miles ($\approx 44\ km$) from coast), and Exclusive Economic Zone (200 Nautical Miles ($\approx 370\ km$)

from coast), which together support fisheries, maritime transport, offshore resources, and coastal livelihoods. These regions are strongly influenced by monsoonal systems, convection, and ocean-atmosphere interactions, making it subject to extreme weather conditions such as thunderstorms and lightning. Figure 1 shows the maritime boundaries of Sri Lanka. According to the reversal of monsoon winds associated with the Inter-Tropical Convergence Zone (ITCZ), Sri Lanka experiences a tropical monsoon climate with two monsoon seasons; Southwest Monsoon (May to September) and Northeast Monsoons (December to February), as well as two inter-monsoon periods; (First Inter-monsoon (March to April) and second inter-monsoon seasons(October to November).

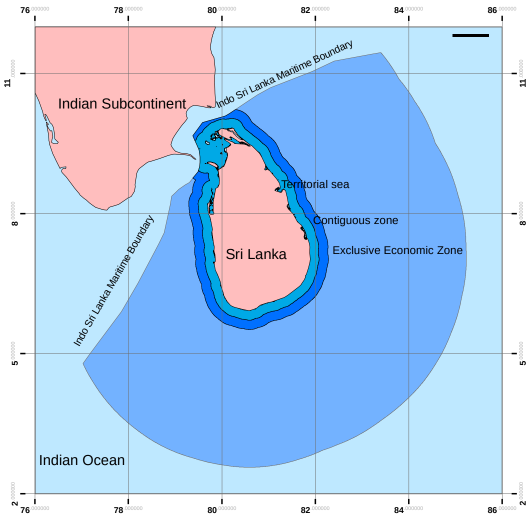


**Figure 1:** Study area including maritime boundaries of Sri Lanka

### 3.2 Lightning Data

The Lightning Imaging Sensor (LIS) was launched in November 1997 aboard the Tropical Rainfall Measuring Mission (TRMM) satellite and remained operational until April 2015. The TRMM satellite followed a low-Earth orbit with a 35° inclination, resulting in less frequent observations near the equator compared to locations closer to the ±35° latitude bands [15]. Due to this orbital configuration, the LIS required a minimum revisit period of approximately 49 days to observe most regions of the Earth at least once during each local solar hour of the diurnal cycle [16, 17]. The instrument observed an area of approximately 600 km × 600 km with a spatial resolution ranging from 3 km to 6 km and monitored individual storm systems for about 80 seconds per overpass. Over Sri Lanka, the satellite passed twice daily during both daytime and nighttime, providing a total observation duration of approximately 160 s $day^{-1}$ [18,19]. The LIS is capable of detecting the spatial location, timing, and radiant energy of lightning events, with detection efficiencies ranging from about 69% near local noon to 88% at night [3]. For this study, total lightning data spanning the period from 1998 to 2014 over Sri Lanka and its surrounding coastal region (5.75°N–10.00°N and 79.50°E–89.00°E) were obtained from [20].

### 3.3 Methodology

This study utilizes a long-term dataset spanning from 1998 to 2014 to analyze lightning activity over the study region. The data were spatially separated and organized using Geographic Information System (GIS) software, allowing accurate extraction of total lightning occurring within defined geographic boundaries. Furthermore, the lightning observations were analyzed using hour-wise (diurnal) data, enabling an assessment of temporal variations and peak activity periods. To investigate temporal interactions among the maritime zones; Territorial Sea(T), Contiguous Zone (C), and Exclusive Economic Zone (E), cross-correlation analysis was conducted using IBM SPSS Statistics 23, enabling the identification of leading and lagging relationships, short term and medium term dependencies, and potential causal patterns among the variables across different maritime zones and monsoon seasons.

## 4. RESULTS

### 4.1 Territorial Sea

The territorial sea is considered as a maritime zone extending up to 12 nautical miles from the country's baseline (Figure 01), within which the state exercises sovereign authority. According to the right of free passage for foreign maritime vessels, this sovereignty involves control over the seabed below and the airspace above. Figure 02 shows the hourly distribution of total number of lightning flashes over the Territorial Sea across four monsoons over a 24-hour period from 1998 to 2014. Overall, lightning activity is low during the early morning hours, increases gradually from midday, and peaks in the late afternoon to evening (around 15:00-20:00 Local Time (LT)), indicating strong diurnal influence.

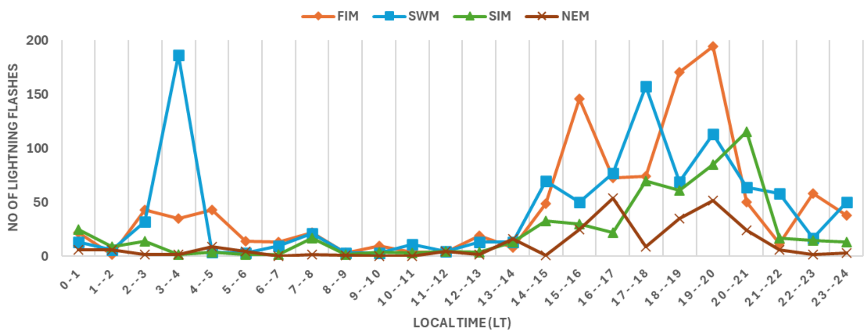


**Figure 2:** Hourly distribution of total number of lightning flashes over the Territorial Sea from 1998 to 2014

The First Inter Monsoon (FIM) and South-West Monsoon (SWM) regions exhibit the highest lightning activity, reaching maximum values of 194 flashes at 19:00-20:00 LT and 186 flashes at 03:00-04:00 LT, respectively. In contrast, the Northeast Monsoon (NEM) records the minimum activity, with values remaining below zero flashes per hour throughout the day. The Second Inter Monsoon (SIM) displays moderate activity with a noticeable evening peak, suggesting regional differences in convective development and storm intensity. Comparatively, minimum lighting activities have occurred during the North-East Monsoon (NEM) over the Territorial Sea area.

Previous study shows that over the landmass, a maximum number of lightning activities have been recorded during FIM [4], and this is mainly entwined with, winds and surface current over Territorial Sea, which leads to increased convectional rainfall and suddenly, leading to strong late afternoon and evening thunderstorms [21]. It may be a risk for small-scale coastal fishing. In SWM, winds blow from the southwest towards the northeast with strong surface currents. Thunderstorms may happen often during night or early morning on the west coast. The analysis indicates that only two lightning flashes were recorded during SIM, whereas no events were observed during NEM, representing the lowest seasonal totals.

### 4.2 Contiguous Zone

The Contiguous Zone is a maritime area extending up to 24 nautical miles from a country's baseline, beyond the Territorial Sea (Figure 01). Figure 03 shows a clear diurnal pattern in lightning activity, with generally low counts during the early morning and midday hours, followed by a sharp increase in the late afternoon and evening (around 17:00-21:00 LT). Over this region, SWM records the highest peak, especially around 20:00-21:00 LT, while FIM and SIM also show strong evening maxima but with slightly lower intensities. Lightning flashes over the Contiguous Zone occurred with very low frequency during the NEM over the period 1998–2014 compared to the other seasons.

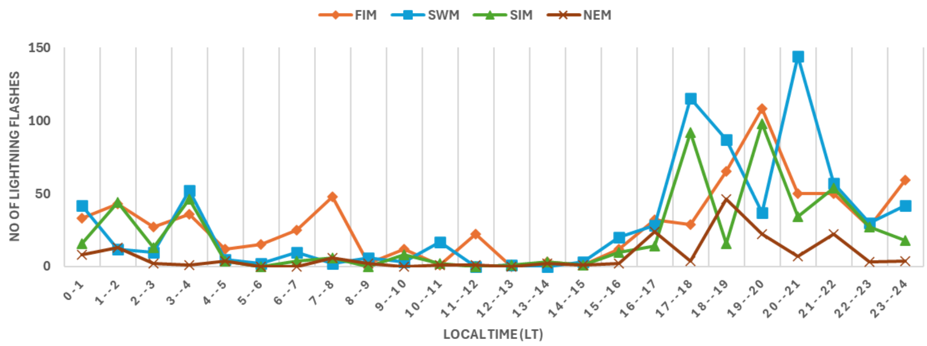


**Figure 3:** Hourly distribution of total number of lightning flashes over the Contiguous Zone from 1998 to 2014

During FIM, over the Contiguous Zone, high solar angle produces strong daytime heating, and strong land heating drives convection that propagates seaward in the evening [22]. In SWM, thick cloud cover reduces daytime solar heating, and often, nocturnal or early morning offshore winds can be experienced. In SIM, due to the high atmospheric instability and moisture content, thunderstorms often occur intensely at night. As well as daytime warming over the aforementioned cause to thunderstorms generation during the night in NEM [23].

### 4.3 Exclusive Economic Zone

An Exclusive Economic Zone is a sea area extending up to 200 nautical miles from a country's coastline (Figure 01) where the coastal state has special rights to explore, use, and manage natural resources. The coastal state controls economic activity, including fishing, energy production, and scientific research while other states are allowed to fly and travel over the Exclusive Economic Zone. Figure 04 shows the diurnal variation of lightning activity across the four monsoons over the Exclusive Economic Zone. SWM dominates overall, with sharp peaks around 4:00-5:00 LT hours and again near 21:00-22:00 LT, indicating periods of intense convective activity. In contrast, the NEM consistently records the lowest lightning counts, suggesting relatively stable atmospheric conditions [24].

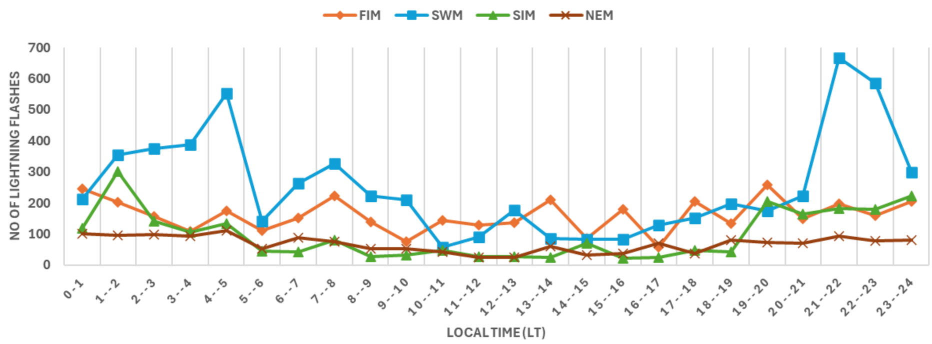


**Figure 4:** Hourly distribution of total number of lightning flashes over the Exclusive Economic Zone from 1998 to 2014

The FIM and SIM show moderate fluctuations, with noticeable increases in the late afternoon and evening, pointing to a diurnal pattern likely influenced by heating and local weather dynamics. Over the Exclusive Economic Zone, strong daytime heating triggers with convective cloud development, causing peaks in the afternoon or night [25].

## 5. DISCUSSION

### 5.1 Cross-Correlation Analysis of Temporal Interactions during FIM

Figure 5 illustrates the cross-correlation analysis of temporal interactions during FIM. The cross-correlation results indicate a strong and statistically significant positive relationship between Territorial Sea over first inter-monsoon (T_FIM) and Contiguous Zone over first inter-monsoon (C_FIM) at lags 0 to 4, with coefficients at lag 0 (0.580), lag 1 (0.639), lag 2 (0.442), lag 3 (0.497), and lag 4 (0.642) all exceeding the 95% significance bounds (approximately ±0.408, calculated as ±2 × standard error), where a lag represents the number of time periods by which one series is shifted relative to the other. The relationship between T_FIM and Exclusive Economic Zone over first inter-monsoon (E_FIM) is statistically insignificant at all lags, as none of the coefficients exceed the 95% significance bounds (±0.408), with the highest value being 0.387 at lag 4. In contrast, C_FIM and E_FIM exhibit a significant positive correlation at lag 0 (0.472), exceeding the critical threshold and indicating a contemporaneous relationship. However, the lack of significant correlations at other lags suggests no clear lead-lag or causal relationship over time. Overall, the findings indicate that T_FIM is an important factor of C_FIM with subsequently positive effects, whereas E_FIM only exhibits a corresponding, inconsistent correlation with C_FIM and no causal relationship with T_FIM.

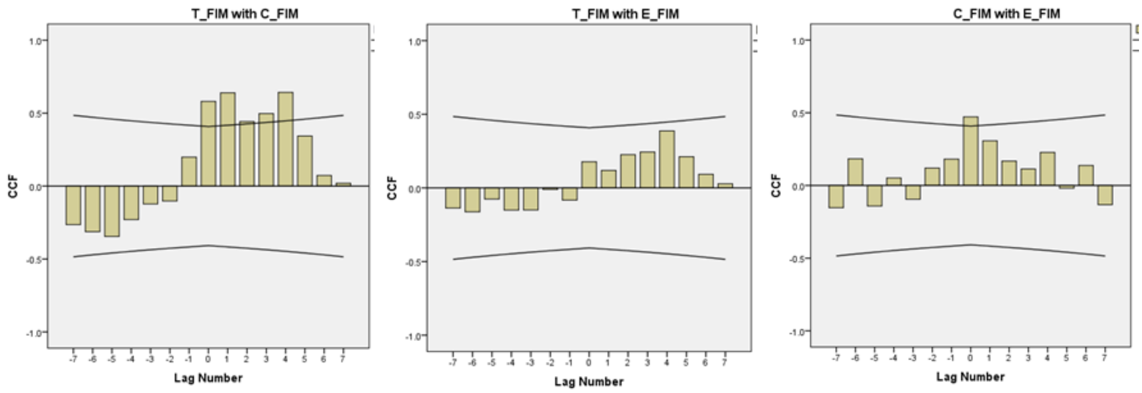


**Figure 5:** Cross-Correlation Analysis of Temporal Interactions during FIM

### 5.2 Cross-Correlation Analysis of Temporal Interactions during SWM

The cross-correlation analysis of temporal interactions during SWM is shown in Figure 6. The cross-correlation analysis for SWM shows that Territorial Sea over South-West Monsoon (T_SWM) and Contiguous Zone over South-West Monsoon (C_SWM) have significant positive correlations at lags 0 ($r \approx 0.60$), 1 ($r \approx 0.52$), and 3 ($r \approx 0.50$), exceeding the ±0.40 (95%) confidence bounds, indicating that T_SWM leads C_SWM by up to three periods with no reverse causality. In contrast, T_SWM and Exclusive Economic Zone over South-West Monsoon (E_SWM) are insignificant at lag 0 but become significant at lags 4 ($r \approx 0.55$) and 5 ($r \approx 0.50$), suggesting a delayed effect, while C_SWM and E_SWM show strong significant positive correlations from lags 1–5 (peaking at $r \approx 0.65$ at lag 4), confirming C_SWM as a leading factor for E_SWM without reverse causality.

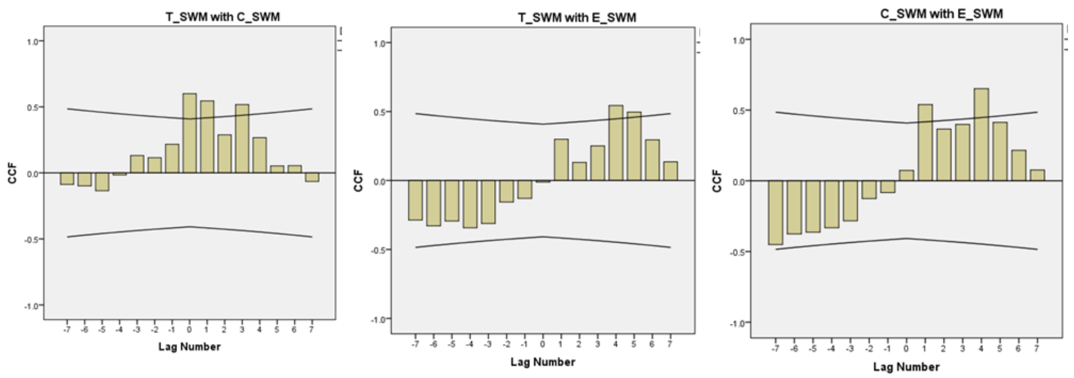


**Figure 6:** Cross-Correlation Analysis of Temporal Interactions during Southwest Monsoon

### 5.3 Cross-Correlation Analysis of Temporal Interactions during SIM

Figure 7 depicts the cross-correlation analysis of temporal interactions during SIM. The results show a statistically significant contemporaneous relationship between Territorial Sea over Second Inter-Monsoon (T_SIM) and Contiguous Zone over Second Inter-Monsoon (C_SIM) at lag 0 ($r \approx 0.62$), with additional significant correlations at lags ±1 ($r \approx 0.55$ and $r \approx 0.48$), exceeding the 95% confidence bounds (±0.40), indicating a short-term bidirectional effect limited to one period. T_SIM and Economic Zone over Second Inter-Monsoon (E_SIM) are insignificant at lag 0 ($r \approx 0.18$) but become significant at lags 2–5 ($r \approx 0.44$–$0.52$), showing that T_SIM leads E_SIM over 2–5 periods. Similarly, C_SIM and E_SIM display significant positive correlations at lag 0 (r ≈ 0.43) and lags 1–4 (peaking at r ≈ 0.60), with no significant negative lags, confirming that C_SIM is a stronger leading indicator of E_SIM without evidence of reverse causality.

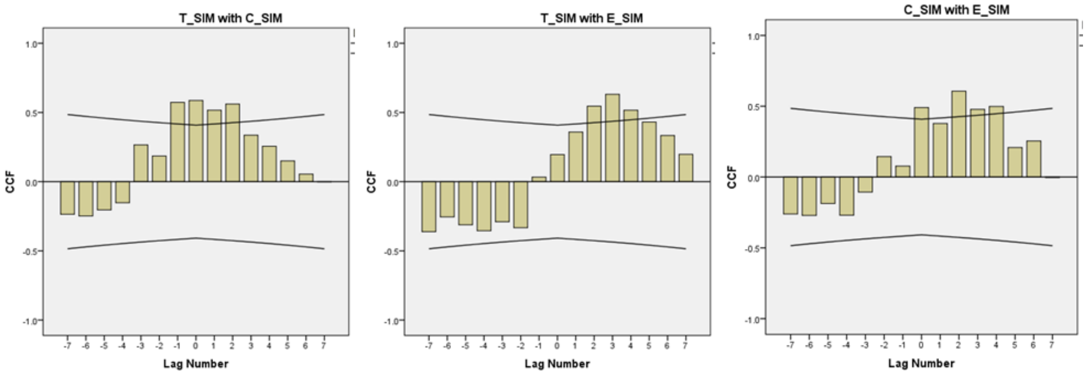


**Figure 7:** Cross-Correlation Analysis of Temporal Interactions during Second Inter-Monsoon

### 5.4 Cross-Correlation Analysis of Temporal Interactions during NEM

Figure 8 illustrates the cross-correlation analysis of temporal interactions during NEM. The cross-correlation results indicate that Contiguous Zone over Northeast Monsoon (C_NEM) and Economic Zone over Northeast Monsoon (E_NEM) have weak contemporaneous correlation at lag 0 (r ≈ 0.10, within the ±0.45 95% confidence bounds), but significant positive correlations at lags 2 (r ≈ 0.32), 3 (r ≈ 0.35), and 5 (r ≈ 0.30), exceeding the upper confidence limit, showing that C_NEM leads E_NEM by about 2–5 periods. For Territorial Sea over Northeast Monsoon (T_NEM) and E_NEM, the correlation at lag 0 is insignificant (r ≈ 0.05), while significant negative correlations appear at lags −4 to −6 (r ≈ −0.50 to −0.60), falling below the lower confidence bound, indicating an inverse relationship where past E_NEM influences current T_NEM; moderate significant positive correlations are also observed at lags 3 and 5 (r ≈ 0.35–0.40). In contrast, T_NEM and C_NEM display a strong and statistically significant contemporaneous correlation at lag 0 (r ≈ 0.70), with additional significant correlations at lags −1 (r ≈ 0.45), 2 (r ≈ 0.60), and 3 (r ≈ 0.55), all exceeding the ±0.45 bounds, confirming strong short-term coupling within one to three periods. Overall, the findings demonstrate a robust short-run linkage between T_NEM and C_NEM, a leading effect of C_NEM on E_NEM over 2–5 periods, and significant delayed partly inverse effects between E_NEM and T_NEM.

This study approaches to improve the current understanding on diurnal variation patterns of lightning activities over the maritime region of the country across the different seasonal periods. This information is critically important to predict thunderstorm weather and as well as to establish some safety precautions to reduce the lightning related accidents in sea areas. Furthermore, reduction of lightning related accidents would enhance production efficiency in the fishing industry and would improve the safety in maritime transportation.

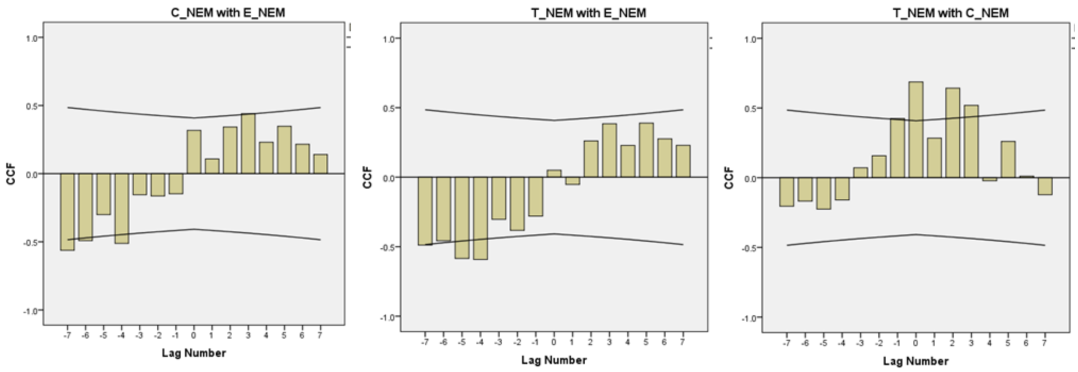


**Figure 8:** Cross-Correlation Analysis of Temporal Interactions during Northeast Monsoon

## 6. CONCLUSION

This study utilizes a long-term satellite-based lightning dataset spanning from 1998 to 2014 to investigate the seasonal variation of lightning activity over Sri Lanka's maritime regions. The results reveal clear diurnal patterns in lightning activity across the maritime zones, with the Territorial Sea peaking at 19:00–20:00 LT (and an early morning peak at 03:00–04:00 LT during the southwest monsoon), the Contiguous Zone showing maxima at 18:00–21:00 LT depending on the season, and the Exclusive Economic Zone exhibiting early morning peaks between 01:00–05:00 LT. Lightning activity is consistently minimal around noon across all zones, providing quantitative evidence of temporal variability influenced by local convection and land–sea interactions. The First Inter Monsoon and South-West Monsoon emerge as the most lightning active periods, particularly over the Territorial Sea (T) and Contiguous Zone (C), while the North-East Monsoon consistently records the lowest lightning activity. Over the Exclusive Economic Zone (E), the South-West Monsoon dominates, with notable nocturnal and early morning peaks associated with offshore convection and large-scale atmospheric circulation. The cross-correlation shows lightning activities in regions T and C act as strong short-term factors of C and E, with T often leading C and C influencing E, whereas E exhibits weaker or inconsistent associations and no evidence of reverse causality. These findings enhance the understanding of seasonal and diurnal lightning variability over maritime regions and provide valuable insights for improving thunderstorm forecasting, maritime safety planning, and risk mitigation strategies, especially for coastal fisheries, offshore operations, and marine transportation.

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