IMPACT OF URBAN INDUCED HEAT ON THE LIGHTNING ACTIVITY OF SRI LANKA: COLOMBO AND SUBURBS

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ABSTRACT: The impact of urban heat islands on the lightning activity of Colombo and suburbs was analyzed using the Lightning Imaging Sensor (LIS) data from December 1997 to April 2015. Lightning is considered the most lethal natural phenomenon because it happens in a short time, and recently, attention has been paid to access the impact of urbanization on lightning activity. In the context of urbanization, urban-induced heat is considered one factor that plays a major role in determining the effects on thunderstorm evolution, dynamics, and resultant lightning activity. Initially, the monthly variation of the lightning flashes for the study area was observed, and a positive trend can be seen along the timeline. To correlate with the urban heat island (UHI) and Urban Thermal Filed Variance Index (UTFVI), the average flash density was mapped, and results show the random distribution and deviation of the hotspot of flash rate density from the city center.

The relationship between the UHI and the flash rate density positively correlates. Further UTFVI index is used to describe the ecological evaluation of urban heat island zones of Colombo and suburbs resulting positive correlation. Although the results are not absolute still, show a positive relationship between the two environmental conditions. To gauge future impacts of lightning on human societies, one must consider how lightning frequency and geographical distribution will be affected by climate change, and superimpose this information on the expected trends in urban development.

INTRODUCTION

With the rapid increase of urbanization over the last decades, there are more observables that urbanizations strongly influence the climatology of the cities and their neighboring areas (Orville, et al., 2001). Urbanization is increasing with the growth of the human population and human activity. As a result, contributed human-made aerosols are increasing, suppressing or strengthening the precipitation process. Many studies have investigated the impact of urbanization on the Cloud-to-Ground (CG) lightning activity from 1970 (Braham, 1974; Huff & Changnon, Jr, 1973; Semonin & Changnon, 1974; Karl, Diaz, & Kukla, 1988; Balling & Idso, 1989). Westcott in 1995 (Westcott, 1995) started to study the effect of an urban area on the initiation and enhancement of CG lightning and ascribed the effect to the urban heat island(UHI) circulation, along with a possible role in air pollution providing ample evidence of these effects based on data from the National Lightning Detection Network(NLDN) in the United States and many studies followed that path (Orville, et al., 2001; Steiger & Orville, 2002; Soriano & de Pablo, 2002; Lal & Pawar, 2011; Wang, et al., 2021). In 2001, Oroville et al. (Orville, et al., 2001)studied the urban effects on lightning, following the path suggested by Westcott (1995). In that study, a long-term analysis was carried out over the city of Houston. The results show the relationship between the urban heat island and anthropogenic pollution in the enhancement of flash density. This association is mainly over the city and the downwind of the metropolitan area.

Furthermore, that study suggested flash rate density increased due to the factors, namely, convergence due to the urban heat island effect and the increasing levels of air pollution from artificial causes. Due to the presence of a physical relationship between lightning activity and convective precipitation in the studies conducted earlier, (Soriano & de Pablo, 2002) analyzed the lightning activity in several small Spanish towns. The data from the Spanish Meteorological Institute collected data from the lightning detection network deployed in the Iberian Peninsula were used in their study. Their results suggested that the higher the concentration of SO_2(Sulfur Dioxide), the higher the number of CG flashes, and the concentration of PM10 portrait the relationship. Simultaneously (Steiger & Orville, 2002) studied the effects of an urban area on the local weather activities using the CG lightning data detected by the NLDN. It has observed a 45% relative enhancement in the flash density compared to other neighboring areas. Concurrently there is a minus twelve percent (-12%) decrease in the positive flash percentage over the city. Furthermore, the authors come up with high negative median peak currents along the coast and into the Gulf of Mexico. This has been explained by hypothesizing that urban heat islands, cloud condensation, and nuclei concentrations are significant factors for enhancing lightning activities.

Since most of the studies were conducted in western cities, the study (Lal & Pawar, 2011) investigated the impact of urbanization on lightning activities over four metropolitan Indian towns. The observations revealed that inland cities are showing considerable lightning enhancement compared to coastal cities. They further explained that large-scale atmospheric operations mainly control the parameters for the lightning activities during the pre-monsoon period than the heat island effect or aerosol effect in the coastal cities.

In 2021, Wang et al. (Wang, et al., 2021)studied the enhancement of Cloud-to-Ground lightning activity caused by the urban effect over Beijing. In that study, abnormal lightning activities were observed over Beijing due to the impact of enhancement of the discharge number in the frontal systems compared to local thunderstorms. In addition, the non-linear relationship between pollutant concentrations and CG flash number has been identified, indicating other factors affecting lighting production (Wang, et al., 2021).

The urban effect is primarily a combination of the thermodynamic effect caused by the urban heat island (UHI) (Wang, et al., 2021) and the increase of pollution concentration due to the plentiful anthropogenic activity. In 2016, Bourschedit (Bourscheidt, Pinto, & Naccarato, 2016) studied the increasing impact of UHI over the cities on the lightning activity was comparatively well understood and the attention to both thunderstorms lifetime and initiation were drawn. Besides, there was no agreement between the pollutants and lightning enhancement.

Even though extensive effects have been taken to study the impact of urban effect on the lightning activities, still the present realization of the topic needs to be investigated comprehensively. When urbanization is increasing the urban sprawl and anthropogenic pollutants emission also increases. On the other hand, increasing the social and economic development of the city also positively contributed to the lightning activities. Most existing studies regarding the urban effect on lightning activity are focused on cities and still, no such study have been undertaken in Colombo being the capital of Sri Lanka. Hence this study focuses on Colombo and an attempt was made to study and gain knowledge of the urban impact on the lightning activities of Colombo. Moreover, the comprehensive understanding of lightning activity with multi-year observation data is also the basis of effective prediction and warning of thunderstorm-related disasters in Colombo City.

STUDY AREA AND DATA

Colombo with its neighborhood area as shown in figure located between 6°41'36" N – 7°40'36" N and 79°50'30" E –80°13'45" E in the southwest of Sri Lanka. The area is covered by the Indian Ocean to its west. Among the provinces in the country, this area is the most densely crowded province in Sri Lanka. One of the primary reasons is, that this area contains the legislative capital Sri Jayewardenepura Kotte and the commercial city, Colombo. This area has been experiencing increasing rainfall during the last few years and as a result, it's becoming vulnerable to flooding. As the most urbanized and commercialized areas of the country, these high streamed climatic events are creating knock-on problems to the area wisely including air pollution, heavy traffic, and high energy consumption demands.

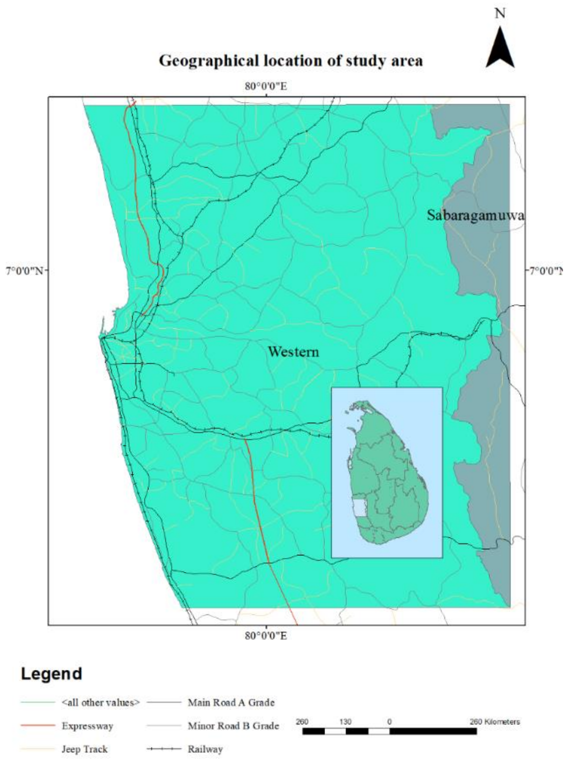


Figure 1: Geographical location of study area

Satellite Data

Landsat 5(TM) and Landsat 8 Landsat Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS) satellite dataset were obtained from the USGS website (https://earthexplorer.usgs.gov). The time-series data from 1997,2001,2003,2009 and 2015 including the visible, infrared, and shortwave infrared, temperature bands were utilized in this study to map the Urban Heat Island (UHI) and Urban Thermal Field Variance Index (UTFVI).

The satellite overpasses the study area between approximately 4:50 and 5:00 GMT which is between 10:20 to 10:30 local time of Sri Lanka. When studying the Land surface temperature, images can be collected in maximum illumination during this time. When using the Landsat level 1 products in the studies geometric correction is not needed to be conducted as those are registered and ortho-rectified. But radiometric correction is needed to conduct to eliminate the errors which may have an impact on the brightness values of the pixels (Fonseka, et al., 2019)

In 1997, Lightning imaging Sensor (LIS) was launched an onboard Tropical Rainfall Measuring Mission (TRMM). The orbit of the TRMM satellite was circular and it has 350 km altitude and 35 degrees to equator inclination (Lambin & Geist, 2003). From December 1997 to April 2015, NASA have being collecting Lighting data based on remote sensing using the instruments which are satellite-based (http://lightning.nsstc.nasa.gov/). The data senses and track down lightning with a storm-scale resolution of 5 -6 km over 35° S to 35° N. LIS has 2ms temporal resolution and during day and night collect cloud-to-ground and cloud-to-ground discharges. The range of flash detection efficiencies measured by the instrument was between 69% to 88% and it detects single storms and storm systems for the period of 80 s. When the storm is in the sensors' field of view, adequate lightning flash rates in the storm can be measured. When downloading data for the selected area which is not monitored during a period of 24 hours capturing a fraction of lightning activities, data were scaled later on to "true" lightning activities. The software used to conduct image processing included ArcGIS version 10.3, and Python. Excel was used for conducting the statistical analysis.

METHODOLOGY

Flash density Computation

In this study LIS lightning data from 1997 December to April 2015 has been used to calculate the cloud to ground lightning flash density over the study area. The raw flash count was divided by the detection efficiency in order to obtain the scaled flash count (Cecil, Buechler, & Blakeslee, 2014). The detection efficiency is available for each hour within a period of the 24-hour cycle.

No flash for a certain day was calculated using the following equation 1 where VT is the view time (in our case 160).

$$Flashes\ per\ day = \frac{86{,}400}{VT} \times \sum SF \tag{1}$$

Then the Flash Density (flashes km^{-2} year^{-1}) was calculated using equation 2 where A is the area considered.

$$Flashes\ Density = \frac{86{,}400}{VT} \times \frac{\sum SF}{A} \times \frac{1}{Years} \tag{2}$$

Usually, Cloud flashes which are mean the flashes which are not terminate at Earth's surface, and Ground flashes were separated by the LIS data. Typically, the ratio between cloud flashes to ground flashes is not constant because this value is varied during the storms. Furthermore, as (Kuleshov, Mackerras, & Darveniza, 2006) LIS data has strong latitude dependence, and in between the latitude from 10° S to 40° S, the most representative long-term value of Z is about 2 ± 30%. Calculated flashes density was multiplied by 0.3 (Sonnadara, Jayawardena, & Fernando, 2019)in order to obtain the ground flash density.
The analysis was further extended by examining the relationship between lightning activities and the UHI and UTFVI in the region. In this study, Landsat 5 and Landsat 8 data has been used to identify the UTFVI and UHI around Colombo city from 1998 to 2015. Due to the cloud coverage of images, images were used with a 4-year gap.

Land Surface Temperature (LST) retrieval

Effective at-Sensor Brightness Temperature

Band 6 from Landsat5 and an average of Band 10 and 11 have been used to retrieve the land surface temperature. The bands were first converted into Radiance (Chander, Markham, & Helder, 2009; Mishra , et al., 2014) using the equation (***Equation 3***) mentioned below.

$$T = \frac{K2}{ln(\frac{K1}{L_\lambda}+1)} \tag{3}$$

Where T is the effective at-satellite temperature (Kelvin), K1 is a calibration constant in W/ (m2.sr. µm), and K2 is another calibration constant in Kelvin. For Landsat 5, Brightness temperature values were used as the LST values and for Landsat 8 emissivity corrected LST was calculated using the following equation 4 developed by ((Stathopoulou & Cartalis, 2009; Weng, 2009).

Land Surface Temperature Estimation

Land surface temperature was estimated using the Equation 4, where LST is in Kelvin (K), BT is the at-sensor brightness temperature (Kelvin), σ = Boltzmann constant which is (1.38 × 10−23 J/K), h is Planck's constant which is(6.626 × 10−34 J/s), c is the velocity of light (2.998 × 108 m/s), and e is the emissivity.

$$LST = \frac{BT}{(\left\{1+W*\left(\frac{BT}{\rho}\right)*ln(e)\right\})} \tag{4}$$

E can be calculated using conditional Equation 5 (Sobrino & Jim`enez-Mu`noz, 2005) and it is assumed that the surface is flat and homogenous (Sobrino & Jim`enez-Mu`noz, 2005). where ε_V and ε_s are the vegetation and soil emissivity, which in this study are 0.98 and 0.92, respectively; PV represents Proportion of vegetation; and C represents the surface roughness (C = 0 for homogenous and flat surfaces), taken as a constant value of 0.005 (Fonseka, et al., 2019).

$$Emmissivity = \varepsilon_{\upsilon\lambda}PV + \varepsilon_{\beta\lambda}(1 - P_{\upsilon}) + C_{\lambda} \tag{5}$$

Mapping Urban Heat Island (UHI)

When there are anthropogenic alterations and influence at the urban boundary layer the effect of UHI arises. By calculating the differences in the average LST between the areas identified as UHI and non-UHI, the UHI intensity can be calculated for the particular area. When the area of urbanization increased, the intensity of the UHI also increases. In this study, we excluded the water bodies because they can influence the temperature significantly. Then UHI was calculated using Equation 6 (Ahmed, 2018)as follows for the study area.

$$UHI = \frac{T_s - T_m}{SD} \tag{6}$$

Where: T_s is the land surface temperature, T_m is the mean of the land surface temperature of the study area, and SD is the standard deviation.

Urban Thermal Filed Variance Index (UTFVI)

UTFVI is used to describe the environmental condition and quality of urban health through the measure of thermal comfort presence in the environment. Finally, the effect of UHI is quantitatively described using the urban thermal field variance index (UTFVI). Using the following equation, UTFVI could be calculated where T_s means surface temperature and T_m is the mean surface temperature (Ahmed, 2018; Liu & Zhang, 2011).

$$UTFVI = \frac{T_s - T_m}{T_s} \tag{7}$$

UTFVI was divided into six levels by six different ecological evaluation indices (Liu and Zhang, 2011, Zhang, 2006). Thresholds in the six UTFVI levels are shown in table 2.

Table 1: Thresholds in the six UTFVI levels (Liu & Zhang, 2011)

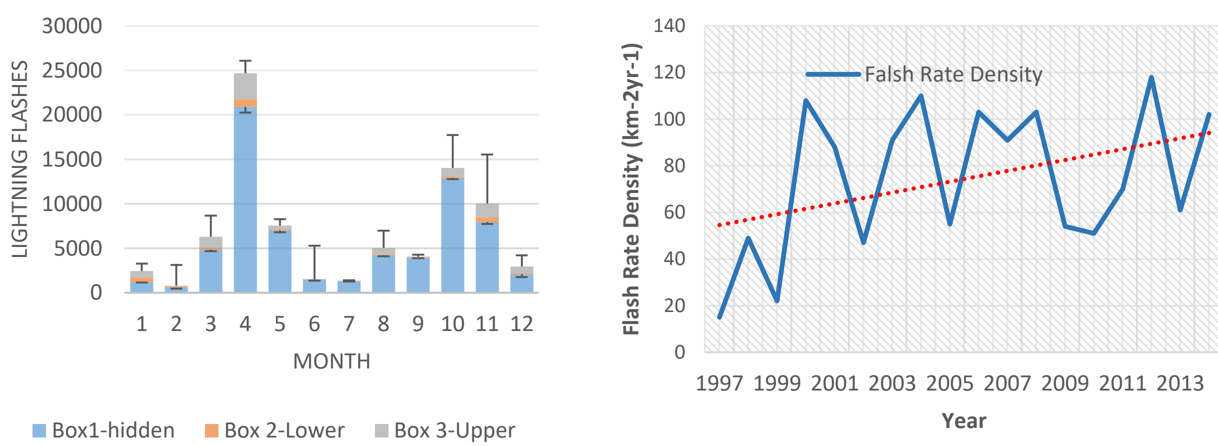
Urban thermal field variation index	Urban heat island phenomenon	Ecological evaluation index
<0	None	Excellent
0.000-0.005	Weak	Good
0.005-0.010	Middle	Normal
0.010-0.015	Strong	Bad
0.015-0.020	Stronger	Worse
>0.020	Strongest	Worst

UTFVI notably causes adverse impacts on different socio-economic and environmental issues, including humidity, air quality, and indirect economic loss, reduced living comfort, and increased mortality rate. When studying the thermal comfort status, studying UTFVI is more attractive. After deriving UHI and UTFVI with Flash rate density correlation analysis was performed to confirm the quantitative approach between two factors.

RESULTS AND DISCUSSION

Box plot of monthly variation of the lightning flashes over 15 years is demonstrated in the Figure 2(a). As shown in Figure 2(a), during the first monsoon period which is April, maximum lightning activities can be seen and during the second inter-monsoon, October expressions higher peak. However, compare to April, October month delivered low amount of lightning activities.

The main reason for the high percentage of lightning activities in the first monsoon is the position of Intertropical Convergence Zone (ITCZ) which is the region of light winds near the equator. It circles the globe making the band of clouds by converging the winds coming from the southern hemisphere and northern hemisphere. ITCZ is positioned over Sri Lanka during monsoons. During the winter period of the northern hemisphere, this cloud band is much broader inducing semi-persistent low-pressure conditions. This cause heavy rain and lightning throughout the island and at many other places at the same latitude (Sonnadara, Jayawardena, & Fernando, 2019). The linear trend of Flash rate density has increasing over the last 15 years as pointed in the Figure (b). Although this linear trend is fitted with the straight line it is still challenging to study the periodicities in the observed variation with a short duration of data.



(a) (b)

Figure 2: (a) Boxplot analysis of annual variation (b) Linear trend of Flash rate density yearly

Since there is an ascending in lightning activities during the last decades, in order to correlate with the UHI and UTFVI, the average flash density was mapped with a 4 year average for the study area. The first and last map only consisted with average of 3 year data. The distribution depicts the random distribution in the output as presented in Figure 3.

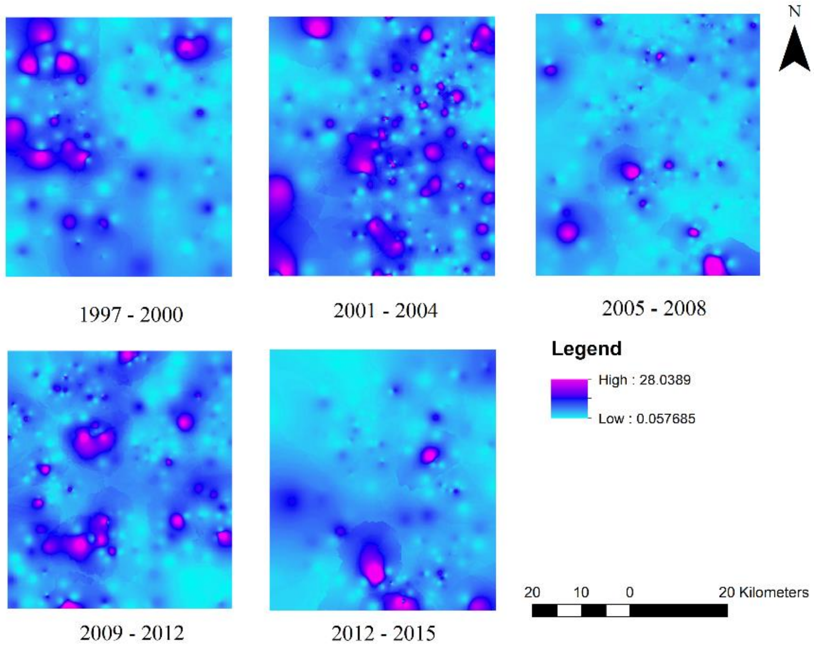


Figure 3: Hotspots of Flash Rate Density for interims

A deviation of the hotspot of flash rate density from the city center along the timeline can be observed in the maps (Figure 3). When considering the mean flash density it has shown highest in the first interim which is 3.41 (Table 2). Although the mean flash density has not confirmed any significant change, the maximum and minimum values of flash rate density have been increased from 1998 to 2015 as detailed in Table 2. For the purpose of correlate with the Flash density, UHI and UTFVI were calculated from the LST temperature.

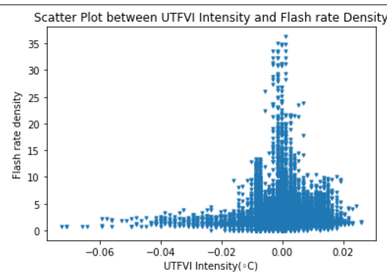
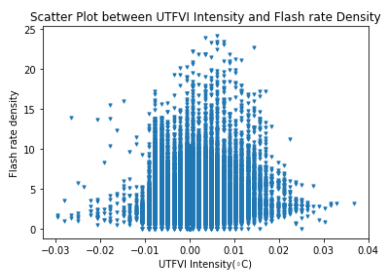
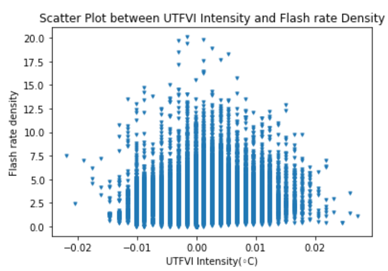
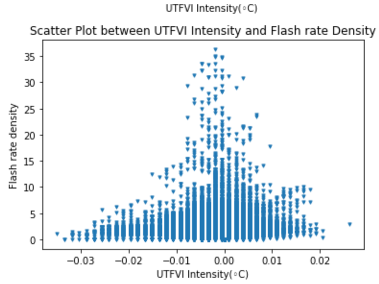
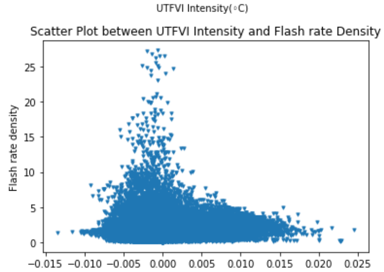
Table 2: Summary of Maximum, Minimum and Mean values of Flash Rate Density and Temperature

Year	Flash rate density			Temperature		
	Min Flash rate Density	Max Flash rate Density	Mean Flash rate Density	Min Temp (K)	Max Temp (K)	Mean Temp (K)
1997-2000	0.030192	20.106716	3.409905	271.848267	301.918427	290.548729
2001-2004	0.042920	21.436546	2.133535	286.929260	305.902130	296.659942
2005-2008	0.049756	24.199326	2.649250	291.532898	306.009766	297.521451
2009-2012	0.057685	28.038918	1.827194	292.186218	307.044739	297.830254
2012-2015	0.077285	36.470119	2.429325	292.489227	314.982208	299.470649

The results indicated that the mean LST was 290.548729 Kelvin in the first four years and it has become 299.470649 Kelvin in the last three years. According to the result, the mean value of the LST is gradually increasing over the time period by 8.9 Kelvin. Similar studies, such as (Fonseka, et al., 2019), have found an increase in LST in the Colombo. A delineated UTFVI map based on UHI is presented in Figure 4. According to the data, there are more rapid temperature changes along the coast than in the country side to the east. However, the results show that the size of the area indicating a poor or worse ecological condition (Table 1) is growing. This is mainly due to the urbanization happening around

Colombo city, creating an urban heat island effect. A temporal analysis is required for the purpose of identification and classification of these persistent features. Overheating of urban areas is common in developing-country megacities as a result of rapid urbanization processes known as UHI. This is defined as the excess warmth in urban areas compared to surrounding rural areas.

Table 3: Statistical Analysis of Correlation

YEAR	SCATTER PLOT	PEARSON'S CORRELATION	SPEARMAN'S RANK CORRELATION
1997-2000		0.16495 Weakly Positive	0.19057 Very Weak Agreement
2001-2004		0.67200 Moderately Positive	0. 25140 Weak Agreement
2005-2008		0.98015 Very High Positive	0. 69501 Strong Agreement
2009-2012		0.67853 Moderately Positive	0. 94002 Strong Agreement
2012-2015		0.34267 Low Positive	0. 47101 Weak Agreement

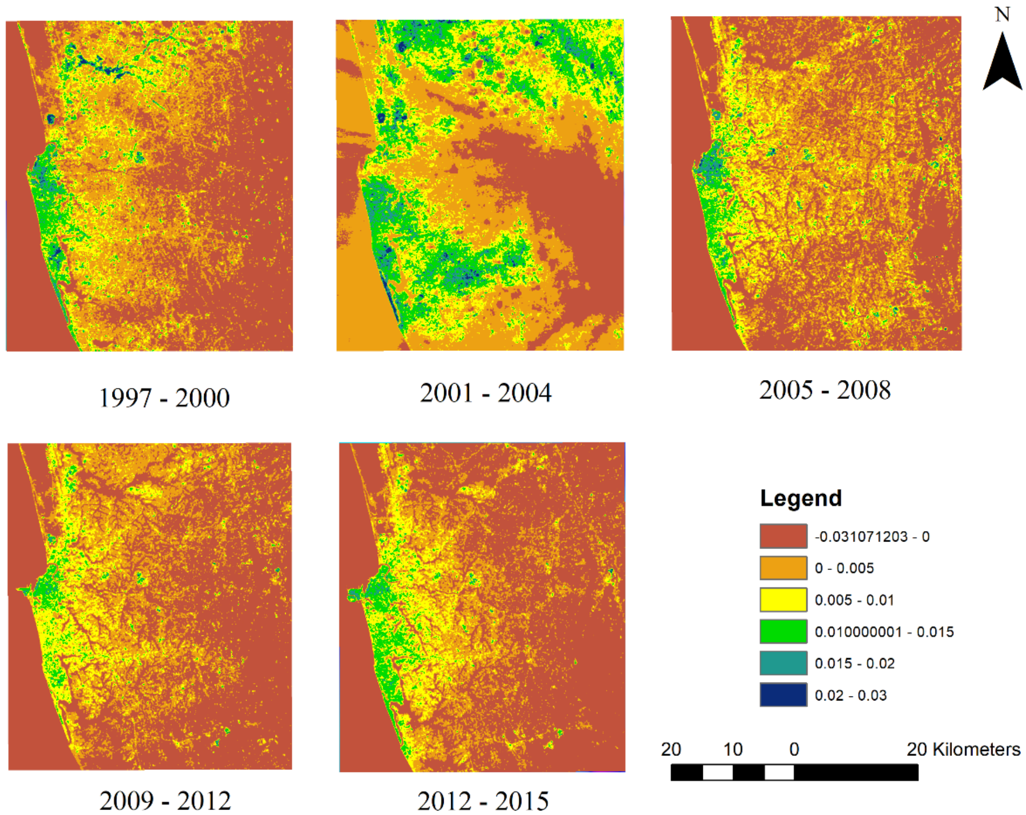


Figure 4: UHI maps of study area for different year interims

Accordingly, this UHI environmental condition is correlated with the flash rate density phenomena to identify the possible impact. The relationship possesses a positive correlation which has become stronger and which is strongest in the interim of 2005- 2008 in Table 3. The scatter plot between mean flash density and UTFVI ranges was drawn to identify the nature of the relationship. When observing the pattern of scatter plot in Table 2, the densified correlation is mostly in the UTFVI range between 0.05 and 0.15. This is the range where UHI is from middle to stronger. For further analysis, the correlations were calculated using Pearson and Spearman rank correlation.

Pearson’s correlation is parametric and Spearman's rank correlation is a non-parametric correlation analysis. In non-parametric calculation, it assesses how well the relationship uses a monotonic function. In Table 3, it shows that both parametric correlations are weak in the first interim and become stronger in the interim of 2005 - 2008, and then weaken again. However, although the thermodynamic effect cannot be fully disregarded, it has been found that the combined effects of the heat island and aerosols have caused a dramatic rise in lightning in this situation (Lal & Pawar, 2011). It suggests that in coastal cities, most of the variables are governed by large-scale processes during the pre-monsoon season. Therefore, neither the heat island effect nor the aerosol effect are noticeable in either of the coastal cities.

Furthermore, Figure 5 shows Flash Rate Density against UTFVI levels. In that figure, under the category UTFVI < 0, which indicates no UHI phenomenon zone, and UTFVI > 0.02, which indicates the strongest UHI phenomena zone, there are fewer occurrences. This implies that when the ecological evaluation index is both excellent and worst, it has fewer existence of lightning. On the other hand, under the category of 0.01–0.015, which is defined as "strong" UHI phenomena, there is a significant number of flash rate density incidents, which implies that when the ecological evaluation index is "bad," there is a significant impact of increasing the lightning occurrences. Similarly, out of six situations, except the two extremes, significant existence happen and it is highest when the index is bad and this is identified as the situation where it needs further attention. If one of the conditions increases, then it will impact the strength of the other environmental conditions, but from one situation it has begun to restraint.

This coincides with the phenomena where urbanization increases overtime simultaneously UHI is also gradually increasing. On the other hand, there is high possibility to increasing the appearance of number of lightning protection equipment with the urbanization. Furthermore, there might be an impact from the lightning rods where there is a dissipation of positive charges when lightning strikes. However, this implies that two environmental conditions, lightning and urban heat island, show a positive relationship but still need to be examined further considering various external factors. The relationship between these two issues needs to be studied and monitored extensively since it has a strong effect on human life. Although Colombo has an obvious UHI, the lightning activity intensity is not significant.

This concluded that the UHI effect is not the only factor in the context of lightning activity and further research is needed to clarify the physical mechanisms that lead to lightning enhancement, such as urban heat island circulation, frictional lift, aerosol increase, cloud water content, etc.

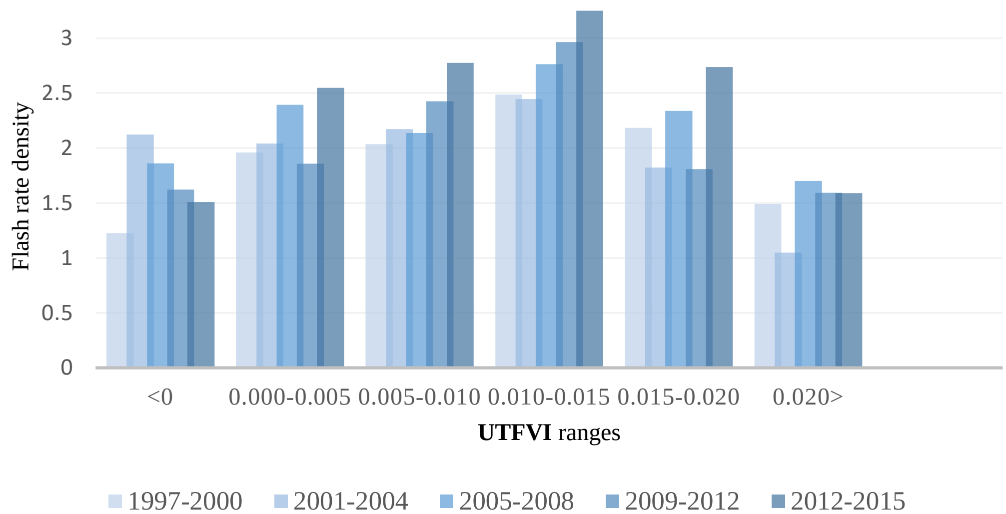


Figure 5: Mean flash rate density for zones of urban thermal field variation index

CONCLUSIONS

In this paper, a 17-year climatological study (1998–2015) of lightning network data in Colombo was presented. To the best of our knowledge, this is the first long-term study reported in the literature related to the role of urban effects on cloud-to-ground lightning in Sri Lanka. The dataset was analyzed from both spatial and temporal perspectives, and the paper also examined the correlation between lightning activity and other parameters, which are UHI and UTFVI. By comparing the spatial relationship between the UHI and the CG lightning density in surrounding cities and industrial areas, the enhancement of lightning activity is influenced by multiple factors. Therefore, longer periods and more precise observational studies from different regions are required.

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