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Correlation analysis between lightning flashes and rainfall rate during a flash flood thunderstorm

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ABSTRACT

This paper presents the correlation analysis between lightning flashes and the rainfall rate of a thunderstorm when a flash flood event happened in Melaka on 11 August 2020. Four types of data have been collected from the electric field mill (EFM), fast antenna (FA) system, constant altitude plan position indicator (CAPPI) radar and world wide lightning location network (WWLLN). Two storms have been detected by the EFM occurred between 04:00:00 and 14:00:00. The FA system recorded a total of 33 lightning flashes had detected with the highest number occurrence of flashes which positive narrow bipolar event (+NBE) around 21 flashes, the maximum rainfall rate and reflectivity have been detected by radar during the first storm were 8 mm h-1 and 37 dBZ, respectively (light rain). During the second storm, there was a total of 980 lightning flashes detected by the FA system with the highest number occurrence of flashes around 429 flashes (IC), the highest value of rainfall rate and reflectivity is 50 mm h-1 and 50 dBZ, respectively (heavy rain). Analyses of the lightning and rainfall rate data also show a close link between the occurrence of major thunderstorms systems and flash flooding on a regional scale.

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1. INTRODUCTION

Malaysia is a tropical country located at the equator's edge at 2°30'N and 112°30'E that have average temperature ranges from 26.5 °C to 27.3 ºC with annual temperature range is very small from 1 ºC to 3 ºC and average of humidity is between 82% to 86%. The geographical location of Peninsular Malaysia is being surrounded by the Andaman Sea, the Sulu Sea, Straits of Malacca and South China Sea might be factors that contribute to the development and increment of thunderstorms and lightning formation [1]. According to the Malaysian Meteorological Services, it has a lot of lightning and thunderstorms, with an average of 200 thunder days each year [2], [3]. Besides, more than 100 times every second, or 8 million times every day, lightning strikes the earth. Previous research conducted in various geographic zones revealed that around 10% of global CG lightning is positive [4]-[10]. This revealed that positive lightning is extremely rare in Malaysia, with the bulk of CG lightning incidents becoming negative. As known, lightning and precipitation are two typical phenomena that frequently co-occur in thunderstorms. It can be very destructive as a result of intense rainfall that occurs over short periods and often results in flash floods.

Many studies showed that the cloud-to-ground lightning flash activities of a thunderstorm could be used in local short term forecasting of heavy rain or precipitation estimation and flash flood or hailstone [11]–[14]. Thus, high precipitation corresponds to strong atmospheric activity in convective systems. Zhou *et al.* [15] showed that the average precipitation and lightning flashes in the main precipitation period are positively correlated with the coefficient=0.86. Total lightning flashes and convective rain during 1998–2010 over South and Southeast Asia exhibited a positive correlation with coefficients 0.68 and 0.81, respectively [16]. Perianan *et al.* [17] studied two tropical hailstorms and their relationship with negative narrow bipolar events (-NBE) and positive ground flashes (+CG) that occurred in Malaysia. Their results found stronger convection does not relate only to higher–NBEs flash rate but also highly correlated to +CGs flash rate. Recent studies by Riduan *et al.* [18] examined the occurrence of large number of +CG flashes during the flash flood happened in Malacca was closely related.

Many researchers have made the correlation of lightning and severe rainfall their subject. Petrova *et al.* [19] found that based on the present study the flash density cannot be used directly for estimation of precipitation in the Mediterranean area. But the strong relationship between rain rate and averaged flash density throughout the continental area during the summer implies that the processes that cause precipitation and lightning are the same. Iordanidou *et al.* [20] investigated the relationship of lightning-rainfall over Crete Island using 22 rain-gauge data and lightning data of CG plus some IC flashes. The results found that the mean lightning-rainfall R could reach 0.6 within a radius of 25-30 km from the center of each lightning cluster. It showed that higher correlations are obtained for more intense rainfall and more flash counts within the searching area.

This paper aims the analysis of the lightning flashes and rainfall rate from a storm when a flash flood event happened on 11 August 2020 in Malacca. The storm happens to cause serious damage and injured many students. The worst-affected locations were Malim, Batu Berendam, Taman Merdeka Permai, and Klebang. Since, the incident happened so sudden, the lightning analysis of a thunderstorm associated with lightning flashes has not been fully studied and discovered. Due to that, it is useful to understand the condition in which lightning storms occur and be able to use this information to eventually improve the forecast of lightning occurrence.

2. METHOD

The data used in this work are obtained from the electric field antenna (EFM), fast antenna (FA) system, constant altitude plan position indicator (CAPPI) radar and world wide lightning location network (WWLLN) for analysis. The lightning data were recorded from a single observation station located in Universiti Teknikal Malaysia Melaka (UTeM), Malacca, Malaysia (2.314077°N, 102.318282°E). Firstly, before processing again with MATLAB software, the EFM data required to be filtered first using code in the MATLAB programme to guarantee data quality and guarantee there were no missing data. The MATLAB software made it simple to analyze the lightning data and determine when the electric field changed the most. Furthermore, the lightning data is collected by using the FA system and the data are saved as the PSDATA file. Picoscope 6 software is used to open the PSDATA file and then analyze the types of lightning flashes based on the waveform detected by the FA system. Picoscope 6 is primarily used to observe and analyze real-time signals captured by Picoscope oscilloscopes and data loggers. The software allocates as much display space as possible to the waveform or waveforms. This ensures that the waveform has the best possible view and that the largest quantity of data is displayed.

The CAPPI radar data have been obtained from Malaysia Meteorological Department (MMD) and the files are in CAPPI format. The radar data in CAPPI format was generated every 10 minutes. The CAPPI was chosen because of its ability to display high-resolution images that can be easily studied. Radar can be used to estimate how hard it is raining. Light rain is defined as reflectivity values below approximately 35 dBZ, moderate rain is defined as reflectivity values between 35 and 50 dBZ, and heavy rain is defined as reflectivity values above about 50 dBZ. Hail is commonly defined as a reflectivity value of more than 55 dBZ. Different colors are used to determine the intensity of the falling rain or snow. While color palettes for precipitation might vary the colors listed which are the most frequently such as Light green (Light rain or rain), Dark green (Light to moderate rain), Yellow (Moderate rain), Orange (Heavy Rain), Red (Very Heavy Rain or Rain & Hail) and Purple (Extremely heavy rain or hail). These data also have been used by many researchers in their studies [17], [18], [21], [22].

The WWLLN is a global lightning detection network that was created through international collaboration, is sponsored by scholars all over the world who host sensors and is coordinated at the University of Washington. It consists of over 70 stations worldwide [23]. The data used in this study that covered the period in 2020 (http://wwlln.net) were extracted from the WWLLN database. For WWLLN data, stroke count data are provided as ASCII text format files. The AE data contains the date and timestamp to the nearest microsecond, latitude and longitude in decimal degrees, and lightning strike energy (J). The area of observation was set to the whole area of Melaka, Malaysia (latitude: 2°11'45.6" N, longitude: 102°14'25.8" E) which the range of latitude was 2 to 2.5 and the range of longitude was 101.9 to 102.6. The time in AE data in Universal time coordinated (UTC) will be converted to Malaysian Standard Time (MYT). Many lightning strikes, coordinate that lightning strike occurred and energy of lightning strike are analyzed. After that, the location of a lightning strike is observed by using Google Earth Pro as shown in Figure 1. Lastly, electric field, lightning flashes, rainfall rate and WWLLN data are correlated.

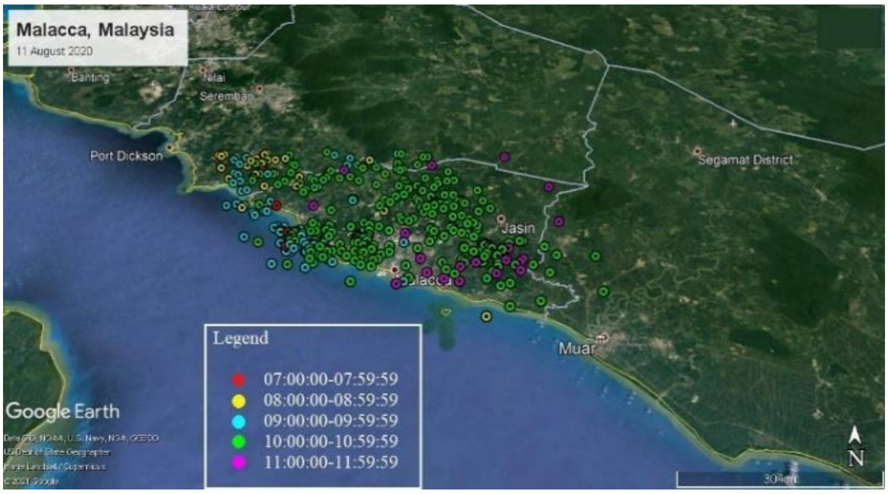


Figure 1. The location of lightning strikes detected by WWLLN on 11 August 2020

3. RESULTS AND DISCUSSION

3.1. Analysis of lightning flashes

A total of 1024 lightning flashes were detected by the FA system in this study. The results show 337 CG lightning events were detected which consisted of 310 were Negative CG (-CG), and the rest of the flashes were Positive CG (+CG). Malaysia is a tropical country on the equator's edge. The Malaysian Meteorological Services were reported many lightning and thunderstorms events with an average of 200 thunder days per year [24]. As discussed by Wooi *et al.* [25], in Malaysia, only 14% to 31% of total CG lightning events were positive lightning, the rest of CG lightning events were negative lightning which was 82%. Chan and Mohamed [26] also examined the occurrence of tropical +CG lightning were 21.91% and 78.09% were -CG flashes in Pekan, Malaysia. This proved that positive lightning is very rare occurred in Malaysia and the majority of CG lightning events are negative lightning. Figure 2 shows the type of lightning flashes detected by two storms on the 11th of August 2020. A total of 33 lightning flashes were detected from the FA system during the first storm. From these 33 lightning flashes, the highest occurrence of lightning flashes during the first storm was +NBE (21), the lowest occurrence of lightning flashes was -NBE (1), and there was no flash was +CG. Moreover, there are 980 lightning flashes detected by the FA system during the second storm. The majority of types of lightning flashes during the second storm was IC around 429 while the minority of types of lightning flashes during the second storm was -NBE around 4.

Figure 3 presents the number of return strokes that was detected by the FA system on the 11th of August 2020 in Malacca. There were 337 CG flashes detected and the maximum number of return strokes detected by the FA system was 14. However, the majority of CG flashes consisted of 1 or 2 return strokes which were 205 and 32 respectively. Only a minority of samples had 13 or 14 return strokes. The maximum number of return strokes was captured by the FA system at 10:06:48 and the range of duration of each return stroke was between 30μs to 80μs.

Figure 4 shows the evolution of flash rate per 10 minutes between 04:00:00 and 14:00:00 on 11 August 2020. During this period, the maximum flash rate was 218 flashes per 10 minutes. The evolution of flash rate was not uniformly which the flash rate rose slightly until the flash rate become 26 flashes per 10 minutes at 05:50:01 then declined slightly. After 07:30:00, it started to become very unstable. It repeated to increase and decrease rapidly around 07:30:00 to 12:00:00. Afterwards, the flash rate was beginning a weakening period from peak maturity before it moved out of the analysis domain.

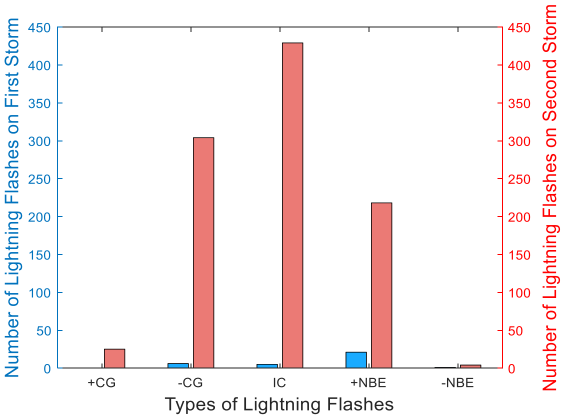


Figure 2. Type of lightning flashes detected by two storms on 11 August 2020

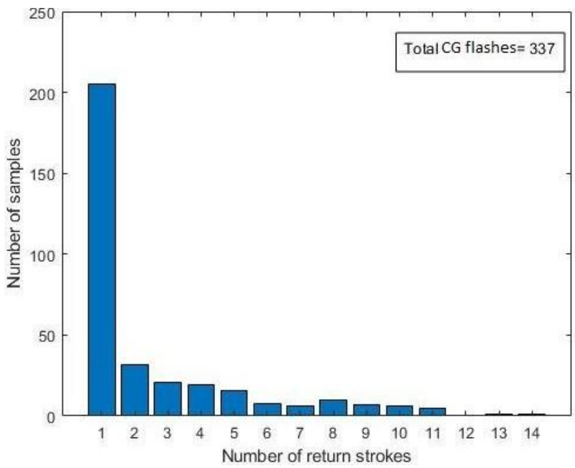


Figure 3. Number of return strokes detected by FA system on 11 August 2020

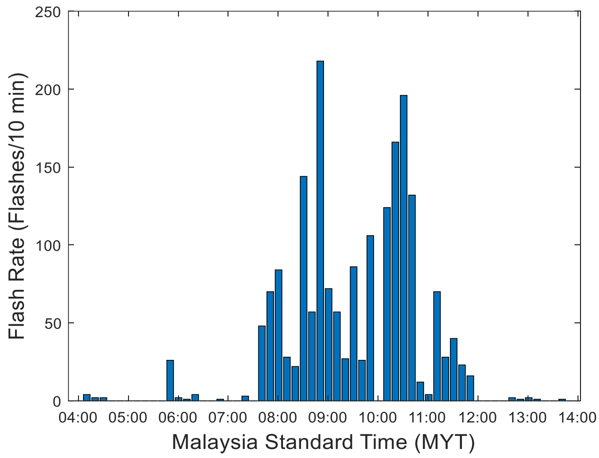


Figure 4. Evolution of flash rate per 10 minutes on 11 August 2020

3.2. Analysis of rainfall rate, reflectivity and its relation to the flash rate

Figure 5 presents the rainfall rate and reflectivity recorded by CAPPI radar on 11 August 2020. The maximum rainfall rate was reached 50 mm/h which was around 9:30:00 to 11:00:00. Surprisingly, the radar reflectivity also reached the maximum values was 50 dBZ at the similar time. Based on the value obtained for rainfall rate and radar reflectivity, heavy rain has occurred during the second storm. Figure 6 shows the location of the lightning strike detected by WWLLN and the active region for the highest reflectivity captured by CAPPI radar. Figure 6(a) shows the majority of lightning strikes were located at Alor Gajah and Melaka Tengah. However, only a minority of lightning strikes were located at Jasin. Based on Figure 6(b), the highest reflectivity value that indicated by the intensity of the color gauge in the CAPPI data. The region where the thunderstorm was reported to have occurred was covered by the active region. Moreover, the location of lightning strikes detected by WWLLN has focused on the active region also. It can be seen also from the radar data the rainfall was started moving from Masjid Tanah and then move to the whole area of Malacca. For the first storm that occurred from 5:00:00 to 7:00:00, the location of the rainfall was moved from Klebang to Ayer Keroh after that to Alor Gajah. Moreover, for the second storm that occurred from 7:00:00 to 14:00:00, the location of the rainfall was started moved from Masjid Tanah and then the whole area of Malacca.

3.3. Analysis of lightning strikes from WWLLN

The lightning strikes were analyzed based on the parameters discussed in Section 2, i.e., the date and timestamp to the nearest microsecond, latitude and longitude in decimal degrees, and lightning strike energy (J). The results, presented in Table 1 show the number of lightning strike detected by WWLLN on the 11th of August 2020. It was found a total of 338 lightning strikes were detected by WWLLN between 07:00:00 and

11:59:59. The highest amount of lightning strikes were recorded between 10:00:00 and 10:59:59 around 225 strikes. However, the lowest amount of lightning strikes was 5 strikes detected between 07:00:00 and 07:59:59. Figure 7 presents the energy of lightning strikes that was detected by WWLLN between 07:30:00 and 12:00:00. It shows that the highest energy of lightning strikes detected was 14.526 kJ at 10:51:51 and the lowest energy of lightning strikes detected was 0.076 kJ. The results show that the maximum strike rate was 70 strikes per 10 minutes which occurred at 10:50:07. The strike rate was unstable until it reached the maximum strikes rate, but after that, it declined sharply.

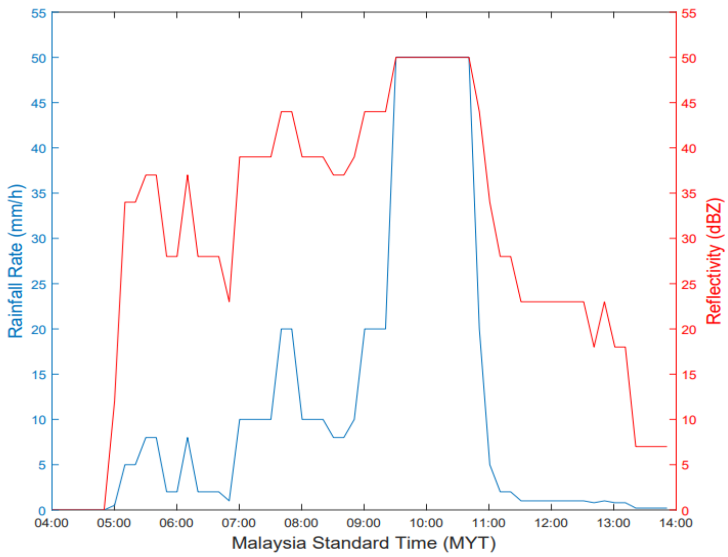
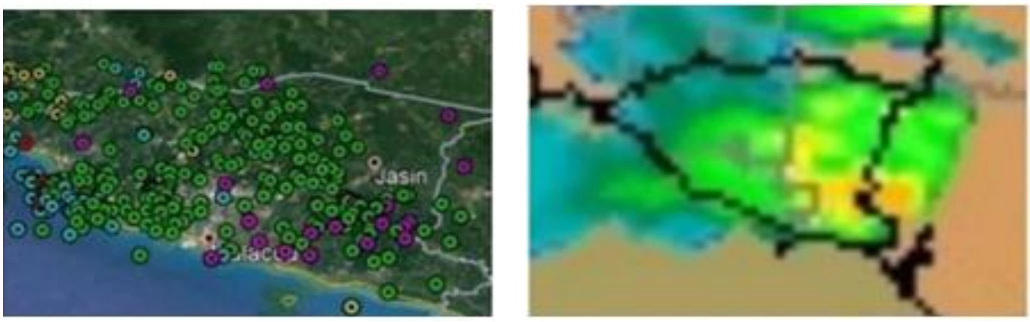


Figure 5. The rainfall rate versus radar reflectivity



(a) (b)

Figure 6. The movement and location of the rainfall for (a) Location of lightning strike detected by WWLLN and (b) Active region for highest reflectivity detected by the CAPPI radar

Table 1. Number of lightning strikes detected by WWLLN

Malaysia Standard Time (MYT)	Number of lightning strikes
07:00:00-07:59:59	5
08:00:00-08:59:59	28
09:00:00-09:59:59	53
10:00:00-10:59:59	225
11:00:00-11:59:59	27

According to the results obtained, it shows that lightning and rainfall are closely related. Figure 8 presents the relationship between flash rate and rainfall rate observed throughout this study. It can be seen when the electric field was higher observed was 9.8 kV/m at 10:48:22, the flash rate and rainfall rate also higher around that time. The flash rate during the first storm that occurred was not stable. The flash rate in the first storm was quite low and the highest flash rate was from 26 flashes per 10 minutes. Besides, the maximum rainfall rate detected by weather radar during the first storm happened was 8 mm/h. At the similar time, the radar reflectivity data revealed that the first storm reached maximum values at 37 dBZ. Based on the value of rainfall rate and radar reflectivity, light rain has occurred during the first storm. During the first storm, the rainfall was moved from Klebang to Ayer Keroh after that to Alor Gajah. Based on the results obtained from WWLLN, there was no lightning strike detected during the period of the first storm happened. The second storm had reached the maximum flash rate was 218 flashes per 10 minutes. Then, after 11:30:00 which was the late stage of the second storm, the flash rate dropped until no flashes per 10 minutes. However, the maximum rainfall rate detected by weather radar during the second storm happened was 50 mm/h. In the meantime, the radar reflectivity data revealed that the second storm reached maximum values at 50 dBZ. Based on the value of rainfall rate and radar reflectivity, heavy rain has occurred during the second storm. During the second storm occurred, the rainfall was started moved from Masjid Tanah and then the whole area of Malacca.

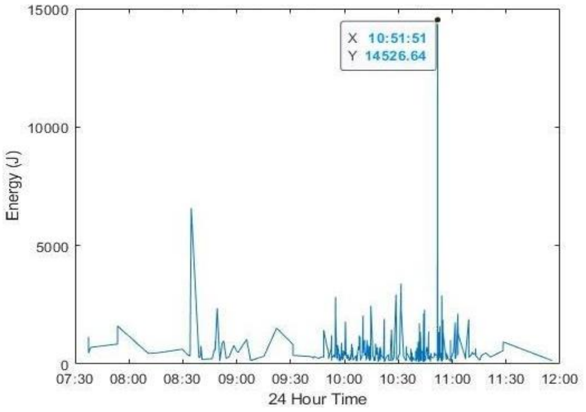


Figure 7. The energy of lightning strikes detected by WWLLN

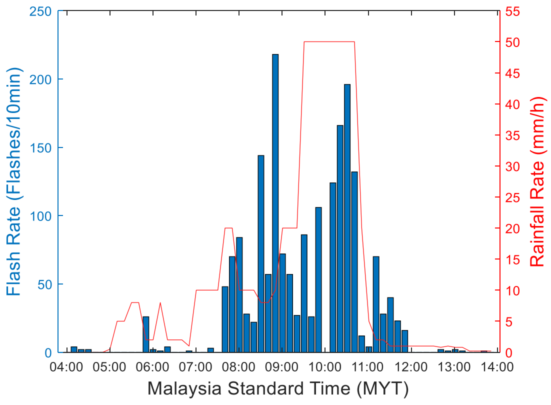


Figure 8. The flash rate versus rainfall rate

4. CONCLUSION

This paper presents the correlation analysis between lightning flashes and rainfall rate on the 11^{th} of August 2020 in Malacca. Two storms have been detected by the EFM system in this study. The first storm happened from 05:00:00 to 06:59:59, while the second storm happened around 07:00:00 to 14:00:00. A total of 1024 lightning flashes were detected by the FA system and the majority of them was IC around 43% of the total flashes. The maximum number of return strokes was captured by FA system at 10:06:48 and the range of duration of each return strokes was between 30µs to 80µs. According to the analysis, it shows that lightning and rainfall are closely related. When the electric field detects maximum was 9.8 kV/m at 10:48:22, after two seconds the highest energy of lightning strikes was detected by WWLLN around 14.526 kJ. At the same time, the value of rainfall rate and reflectivity also shows highest around 50 mm/h and 50 dBz, respectively. More intense rainfall and more flash counts were expected to happen during the second storm and it produces a huge amount of IC flashes throughout the observation.

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