Polar Science 20 (2019) 84–91

Contents lists available at ScienceDirect

Polar Science

journal homepage: www.elsevier.com/locate/polar

Cloud-to-Ground lightning observations over the Western Antarctic region

Norbayah Yusop[a,b,*], Mohd Riduan Ahmad[b], Mardina Abdullah[c,d], Siti Khalijah Zainudin[a], Wan Nur Arina Wan Mohd Nor[a], Kemal Maulana Alhasa[a], Mona Riza Mohd Esa[e], Muhammad Haziq Mohamad Sabri[b], Wayan Suparta[f], Adriana Maria Gulisano[g,h,i], Vernon Cooray[j]

[a] Space Science Centre (ANGKASA), Institute of Climate Change, Universiti Kebangsaan Malaysia, 43600, Bangi, Selangor Darul Ehsan, Malaysia
[b] Atmospheric and Lightning Research Laboratory, Centre for Telecommunication Research and Innovation (CeTRI), Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100, Durian Tunggal, Melaka, Malaysia
[c] Institute of Climate Change, Universiti Kebangsaan Malaysia, 43600, Bangi, Selangor Darul Ehsan, Malaysia
[d] Centre of Advanced Electronic and Communication Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan, Malaysia
[e] Institute of High Voltage and High Current (IVAT), Universiti Teknologi Malaysia (UTM), 81310, Skudai, Johor Bharu, Malaysia
[f] Department of Informatics, Pembangunan Jaya University, South Tangerang, Banten, 15413, Indonesia
[g] Instituto Antartico Argentino (DNA), Cerrito, 1248, Buenos Aires, Argentina
[h] Instituto de Astronomia y Fisica del Espacio (UBA-CONICET), Argentina
[i] Departamento de Fisica, FCEyN, Universidad de Buenos Aires, Argentina
[j] Ångström Laboratory, Division for Electricity, Department of Engineering Sciences, Uppsala University, Box 534, S-75121, Sweden

A R T I C L E I N F O

Keywords:
Antarctic
Cloud-to-ground flash
Flash rate
Stroke multiplicity

This paper presents the observations and characterization of Cloud-to-Ground (CG) lightning activity in Western Antarctica in a region that covers the Amundsen/Bellingshausen Sea (ABS), the Antarctic Peninsula (AP) and the Weddell Sea (WS). Lightning data have been collected by a lightning detector (Boltek LD-350) and an atmospheric electric field mill (EFM-100) sensors deployed at the Carlini Base on the Antarctic Peninsula (CARL: 62.23°S, 58.63°W). The flash rate and flash multiplicity were analysed for three different seasons within a 1,000 km range, starting at the end of summer (February 2017) and ending in winter (July 2017). Three storm days for each month (within the 1,000 km radius from the LD sensor) with three composite active thunderstorms (labelled as Storm region A, B, and C) for each day have been selected from a collection of storm days between February and July 2017. A total of 355,899 flashes have been recorded with 156,190 Positive CG and 199,709 Negative CG flashes from these 54 thunderstorms. In total, Positive CG flash counts made up around 43.9% of the total detected CG flashes. Most of the Positive CG flashes (> 80%) had only 1 or 2 strokes with a maximum number of 5. For Negative CG flashes, the average multiplicity and the maximum multiple stroke were 1.2 and 16 respectively. Most CG flashes were detected during the summer and fall months. Positive CG flashes were prevalent in Western Antarctic storms even during the winter. The mean, median and range of the ratio of Positive CG to Negative CG flashes were 0.7, 0.718 and 0.217–1.279, respectively.

1. Introduction

Cloud-to-Ground (CG) lightning flashes are the most common type of lightning flash has and have been studied extensively. In general, around 90% of CG flashes are negative CG (–CG) flashes with the remaining 10% being positive CG (+CG) flashes (Rakov, 2003; Akinyemi et al., 2014; Dwyer and Uman, 2014; Cooray, 2015). Both CG flash types play a significant role in lightning protection and atmospheric physics. As discussed by Qie et al. (2006), the features and characteristics of CG flashes are very significant in understanding the mechanism of lightning and the development of lightning protection systems.

The electric field temporal characteristics of CG flash waveforms and the occurrences of CG flashes have been studied extensively. The most recent study by Johari et al. (2017) characterized +CG flashes focusing on the electric field produced by the first and subsequent return strokes in Sweden. They found 88% of the flashes were single-stroke while 12% were multiple-stroke. Baharudin et al. (2016) also

* Corresponding author. Space Science Centre (ANGKASA), Institute of Climate Change, Universiti Kebangsaan Malaysia, 43600, Bangi, Selangor Darul Ehsan, Malaysia.
E-mail address: norbayah@utem.edu.my (N. Yusop).

https://doi.org/10.1016/j.polar.2019.05.002
Received 15 May 2018; Received in revised form 26 April 2019; Accepted 7 May 2019
Available online 08 May 2019

reported the stroke characteristics of +CG flashes in Sweden. They found a total of 107 flashes having a maximum of four strokes. Hazmi et al. (2016) reported the characteristics of multiple-stroke –CG lightning flashes in Padang, Indonesia. They examined 100 –CG flashes comprising 623 strokes with an arithmetic mean (AM) of 5.2 and maximum number of strokes of 18. The authors reported that all first-return strokes were preceded by initial breakdown pulses. Similar observations have been reported by M. Zikri et al. (2018) based on a magnetic field measurement system in Melaka, Malaysia. The authors found that all the first return strokes were initiated by initial breakdown pulses.

Zhu et al. (2015) examined characteristics of –CG flashes at the Lightning Observatory in Gainesville (LOG), Florida. They examined important parameters of lightning flashes such as the flash multiplicity, interstroke interval, flash duration and first-to-subsequent stroke field peak ratio in their analysis. The average number of strokes per flash was 4.6 and the interstroke interval, flash duration and first to subsequent stroke field peak ratio were around 52 ms, 223 ms, and 2.4 respectively. Yair et al. (2014) presented stroke data obtained from the Israel Lightning Location System (ILLS). The average multiplicity of –CG flashes was around 1.4 and the percentage of single stroke flashes was 58%. Nag and Rakov (2012) examined 52 +CG flashes containing 63 strokes recorded between 2007 and 2008 in Gainesville, Florida. The average multiplicity was 1.2 and the single stroke flashes accounted for around 81% of the flashes. Fleenor et al. (2009) examined the characteristics of –CG and +CG flashes in the Great Plains. A total of 204 +CG flashes were detected with 210 strokes and an average multiplicity of around 1.04, while a total of 109 –CG flashes were obtained with 296 strokes. Saba et al. (2006) determined the properties of –CG lightning using digital high-speed video in their observations. They found that 20% of the –CG were single-stroke flashes and the average multiplicity was 3.8. Heidler and Hopf (1998) reported the measurement of the electric field of CG flashes in Germany. A total of 44 +CG flashes were detected with an average multiplicity of 1.3.

Studies on the CG flashes have been conducted extensively in various regions. However, no or very few studies have been carried out in polar regions such as in Antarctica. A recent study regarding Antarctic cloud properties by Adhikari et al. (2012) classified Antarctic clouds into four types: high level cloud (cloud base ≥ 6 km and cloud thickness < 6 km), middle level cloud (2 ≤ cloud base < 6 km and thickness < 6 km), low level cloud (cloud base < 2 km and thickness < 6 km) and deep cloud (thickness ≥ 6 km and cloud base < 2 km). The study was based on data collected from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and CloudSat satellites between June 2006 and May 2010. The Amundsen/Bellingshausen Sea region (ABS), which is located on the western side of the Antarctic Peninsula, was observed to have the highest cloud occurrence (more than 80%). Interestingly, the authors found that cloud top height of high-level cloud and deep cloud in the Western Antarctic region (refer to their Fig. 7 page 9 and Table 1 page 10) could reach up to 10.3 km and 9.1 km respectively during the winter, and 10 km and 8.6 km respectively during summer. The cloud thickness of the deep cloud of Western Antarctic region could reach up to 7.6 km during the winter and up to 7.2 km during the summer. It could be suggested that the deep cloud structure (winter and summer) is similar to the cloud in Sweden (Ahmad et al., 2015) during the summer with low cloud tops.

Ahmad et al. (2015) discussed the role of the shape and size of thunderstorms in the production of +CG flashes in high latitude regions. Often, in a tropical thunderstorm, the main positive charge centre is screened from the ground by the main negative charge centre and this pattern is influenced by the shape and size of the thunderstorm (with narrow, elevated mixed-phase regions, higher cloud tops, and slim shapes for hot tower thunderstorms). This in turn could explain why +CG flashes are very rare in the tropics. On the other hand, high latitude storms are generally thicker with lower cloud tops, e.g. around and less than 12 km for summer storms in Sweden. Therefore, the main

Table 1
Comparison of positive ground flashes with different number of strokes.

Researcher	Location	Measurement period	Sample size, N	Occurrence of flashes with number of strokes					Average multiplicity
				Single stroke	Two strokes	Three strokes	Four strokes	Five strokes	
Present study (2018)	**Carlini Base, Antarctica**	**Feb-July 2017**	**156190**	**139280 (89.173%)**	**15564 (9.965%)**	**1273 (0.815%)**	**67 (0.043%)**	**6 (0.004%)**	**1.1**
Present study (2018)	**Malacca, Malaysia**	**14 Sept 2016**	**102**	**69 (67.65%)**	**17 (16.67%)**	**12 (11.76%)**	**4 (3.92%)**	**0**	**1.5**
Johari et al. (2017)	Uppsala, Sweden	Summer 2014	51	45 (88%)	4 (8%)	1 (2%)	1 (2%)	0	1.2
Baharudin et al. (2016)	Uppsala, Sweden	Summers of 2010 and 2011	107	67 (63%)	30 (28%)	7 (6%)	3 (3%)	0	1.5
Nag and Rakov (2012)	Florida, US	Apr–Oct and Nov–Feb 2007–2008	52	42 (81%)	9 (17%)	1 (2%)	0	0	1.2
Saba et al. (2010)	Brazil, US and Austria	Feb 2003, Sept 2009	103	83 (81%)	19 (18%)	1 (1%)	0	0	1.2
Fleenor et al. (2009)	U.S. Central Great Plains	July 2005	204	195 (96%)	9 (4%)	0	0	0	1.04
Heidler et al. (1998)	Munich, Germany	1995–1997	32	28 (87.5%)	4 (12.5%)	0	0	0	1.13
Heidler and Hopf (1998)	Munich, Germany	1984–1993	44	33 (75%)	8 (18%)	2 (5%)	1 (2%)	0	1.3

positive charge centre is not screened from the ground and this in turn is why +CG flashes are prevalent in high latitude storms (Rakov and Uman, 2003; Dwyer and Uman, 2014). In other words, tropical storms produce less +CG flashes compared to high latitude storms.

In this paper, the characteristics of both +CG and –CG flashes are examined and analysed using lightning detector (LD-350) and an electric field mill (EFM) sensor installed at Carlini Base on the Antarctica Peninsula. The flash rate, flash multiplicity and the percentage of single-stroke CG flashes are discussed in this paper. Selected days from February to July 2017 have been chosen based on the maximum values of electric field recorded by EFM-100 for the analysis. To the best of our knowledge, this is the first comprehensive study on lightning characterization of both +CG and –CG flashes in this polar region and it may give useful information on lightning activity and charge structure of thunderclouds in this region.

2. Instrumentation and methods

2.1. Measurements

The measurements were taken with a Boltek Lightning Detector LD-350 and EFM-100 installed at Carlini Base on the Antarctic Peninsula as shown in Fig. 1(a) and Fig. 1(b). Fig. 2 shows the location of the Carlini Base station at Antarctic Peninsula in this study. The LD-350 operates based on the Magnetic Direction Finder (MDF) technique to locate the source of lightning pulses. It measures the radiated impulse from the discharges. It also used for a long range lightning detector which able to plot strike locations and provide a relevant strike information in the range of about 480 km. If there are intense storms, it can detect lightning pulses over 960 km away. Nextstorm Lite is a software used to perform calculations, to draw strike and storm symbols on a map, analyse the stroke signal wave shapes, and to count strikes. It is a stable, reliable and highly accurate in terms of lightning locating accuracy. The LTS-3 timestamp card is present on the LD-350 to capture the exact time when the lightning signal was received. The data are timestamped with an accuracy of hundreds of nanoseconds using a high accuracy timing GPS receiver (Boltek Corporation, 2012).

The EFM-100 is used for short-range detection of nearby thunderstorms up to 30 km away. The EFM-100 is a high quality atmospheric electric field detector which can monitor and record data. It not only detects nearby lightning but can also detect the high electric field conditions which precede lightning. It is designed to provide a real time reading of the electric field in the atmosphere with a time versus electric field graph displayed on a computer along with lightning strike distances accurate to within 1.6 km. Maximum and minimum measurable values of electric field strength are ± 20,000 V/m and the response time is 0.1 s (twenty readings per second) (Boltek Corporation, 2016).

The data from tropical storm in Malaysia on September 14th, 2016

Fig. 1. Measurement installed at Carlini Base for a) lightning detector (LD-350) and b) electric field mill (EFM-100).

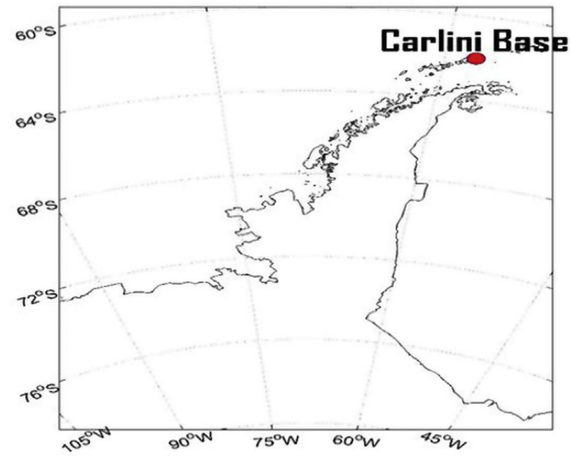

Fig. 2. Location of Carlini Base station at Antarctic Peninsula in this observation.

was recorded from a single observation station hosting a wideband fast and slow electric field antennae system (decay time constant 13 ms and 1 s), magnetic field sensor (400–4000 Hz) (Zhang et al., 2016) and a VHF sensor (40–80 MHz) with a centre frequency of 60 MHz. The station is located at the Universiti Teknikal Malaysia Melaka (UTEM), Malacca, Malaysia (2.314077° N, 102.318282° E). The output of the antennas is digitized at rates of 20 MS/s for 3 channels (fast and slow E-field and dB/dt) and 250 MS/s for 2 channels (fast electric field and VHF sensor) with a resolution of 12 bits and 8 bits. Data records were event-triggered and were 0.5 s long. The timing for each event was provided by a GPS. Additional details of the E-field instrumentation are given in Ahmad et al. (2014) and Esa et al. (2014). The observations presented here were obtained from a single storm producing many +CG flashes close to our system on September 14th, 2016.

2.2. Data processing

In this study, we used the data collected from the LD-350 and EFM-100 on the Antarctic Peninsula for analysis. In order to process the LD data, it needs to be converted first from *.nex to *.txt files using the Windows command line (DOS) prompt software. The data consists of the timestamp in seconds, the bearing to strike, corrected distance to strike, strike type and strike polarity which is useful when studying the characteristics of the lightning flashes in the Antarctic Peninsula. The EFM-100 data need to be filtered first using code in the MATLAB programme to ensure the quality of the data and to make sure there are no missing data before processing again using MATLAB software. The WWLLN data was confined by -50^{o}S to -80^{o}S and -30^{o}W to -90^{o}W cover all strikes displayed from the LD system in 2017 as shown in the dark blue area in Fig. 3. Data have been analysed for three selected days for each month (altogether 54 storms) having maximum electric fields on the 12th, 16th, 26th February, 18th, 27th, 31st March, 1st, 4th, 8th April, 1st, 19th, 30th May, 15th, 20th, 26th Jun and 10th, 11th, 12th July 2017 due to the presence of storms and lightning activity nearby captured by the LD-350 and EFM-100 sensors. The EFM data were used to analyse the diurnal variation of atmospheric electric field using 1-min averages to avoid rapid changes in field for the analysis reported here. It was also used as a proxy to support the events through the lightning statistical analysis in this study. From the LD data, the type and polarity of strikes were given in digital format 0 or 1 (CG or IC) and 0 or 1 (positive or negative), respectively. Then, both return strokes underwent classification in order to determine one complete flash within 1 s.

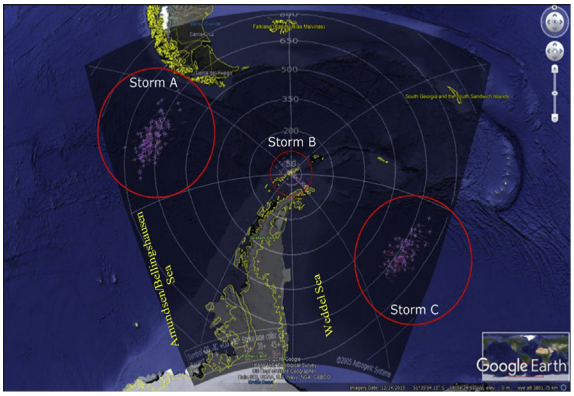

Fig. 3. The area and location of strikes captured by the lightning sensor (LD-350).

2.3. Storm location

All selected 54 storms within the six-month period of observation at Carlini Base station were located in three regions as displayed in Fig. 3. The area and location given are obtained from the screenshot of LD-350 on 21 February 2017. The screenshot was displayed every 1 h. Analyses in this study have been made based on three Storms region A, B and C. These represent composite storms made up from several other storms occurring in one day. Storm region A was located to the northwest (N/W) of Storm region B and Storm region C was located to the southeast (S/E) of Storm region B with a distance range from 500 to 800 km. Storm region B was located very close to the Carlini Base station with distance range and angle taken within 100 km and 0°–360°, respectively.

Fig. 4 shows more detail example of three storms on March 27th, 2017 (4a, top) together with EFM record (4b, middle). Fig. 4(a) shows the locations of Storms region A, B and C similar to the plot in Fig. 3. The centre of the circle is the location of the sensor at Carlini Base. The farthest detected flash was 881 km from the sensor. Fig. 4(b) illustrates the electric field mill record starting from 22:00:00 to 24:00:00 ART (Argentina Time) in the range below 30 km on March 27th, 2017. The maximum electric field was recorded around −20 kV/m at 22:03:00 ART. The maximum electric field records due to the strong thunderstorm event have been detected closest to the station. Fig. 4(c) shows the number of CG strikes detected within 1,000 km from the sensor. A higher number of CG strikes was within 200 km of the sensor; 4,126 were observed. Around 232 CG strikes were observed between the ranges 500–900 km from the sensor.

3. Results and discussion

The distribution of the number of lightning strikes in 2017 recorded by the LD system was compared to the World Wide Lightning Location Network (WWLLN) as shown in Fig. 5. Overall, a total of 1.12 × 10^8 lightning strikes were recorded by the LD compared to only 17,648 lightning strikes detected by the WWLLN system. Fig. 5(a) and (b) show the monthly distribution of the number of lightning strikes detected by the WWLLN and the LD system, respectively. The WWLLN system recorded higher number of lightning strikes in January and February with 3,936 and 4,282 strikes, respectively. However, for the rest of the months, less than 2,000 strikes were recorded by the system. Obviously, for the LD system the highest number of lightning strikes was detected in the three continuous months of February, March and April with about 30,704,252, 34,671,872 and 45,511,286 strikes, respectively. In contrast, the rest of the months showed the lowest value of less than 240,000 strikes which was not displayed in the graph due to the small value and while zero value was obtained in January as no LD data was available.

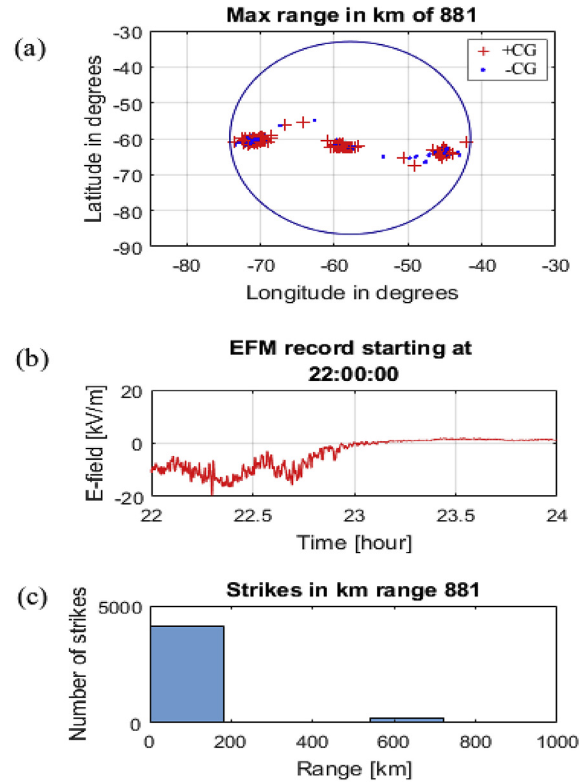

Fig. 4. Three storms detected by the LD system with high electric field on March 27th, 2017 (a) Location of + CG and –CG strikes, (b) Electrostatic field at the ground on March 27th, 2017 and (c) Histogram of the number of all CG strikes within the detected range.

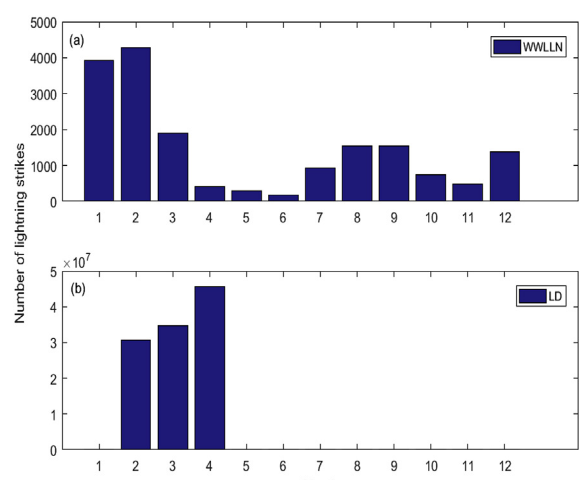

Fig. 5. Distribution of the number of strikes recorded by (a) WWLLN and (b) LD network in 2017.

The comparison revealed that the detection efficiency of the LD system is approximately six thousand times higher than the WWLLN system relative to the total number of lightning strikes throughout the analysis. The LD sensor coverage is capable of capturing lightning strikes from 480 to 960 km which is much more precise when compared to the WWLLN which is above 10, 000 km from the receivers (Rodger et al., 2017). The time accuracy used by the LD system is 100 ns which is considered higher in terms of exactly capturing the time of the lightning signal received (Boltek Corporation, 2012). Recent studies have found the WWLLN is able to detect lightning locations accurately to within about 5 km with timing accuracy of 15 μs and an estimated overall stroke detection efficiency of 11% (Hutchins et al., 2012a; Abarca et al., 2010; Rodger et al., 2009). Rudlosky and Shea (2013) found WWLLN detection efficiency of 6.0% for 2009, 6.8% for 2010, 8.1% for 2011, and 9.2% for 2012 in the Western Hemisphere between 38°N and 38°S. Therefore, the capabilities of the LD system in terms of the detection efficiency, coverage and time accuracy are considered higher and more precise than the WWLLN system in capturing the lightning strikes in the Western Antarctic region.

The flash rate and flash multiplicity were analysed for three different seasons in an area within 1,000 km of Carlini Base on the Antarctica Peninsula, starting at the end of summer (February 2017) progressing towards fall and ending in the winter (July 2017). Three storm days (within 1,000 km radius from LD sensor) with three composite thunderstorm areas (Storms region A, B, and C as shown in Fig. 3 have been selected from a collection of storm days within each month. These thunderstorms were chosen based on the good record of EFM on that particular day. Therefore, for the six-month period from February to July 2017, a total of 54 thunderstorms have been chosen for the analysis purposes. A total of 355,899 flashes were recorded with 156,190 +CG and 199,709 –CG flashes from these 54 thunderstorms.

Fig. 6 shows the evolution of monthly flash rate for +CG, –CG and the total of both +CG and –CG. The monthly flash rate values for total CG is depicted with a symbol 'x' and connected by short dashed line. The monthly flash rate values for +CG and –CG are depicted with symbols of 'o' and '-' connected by solid and dashed lines, respectively. The values given on the lines between the symbols are the flash rate ratio. The flash rate ratio is calculated based on the value of the current month divided by the value of the previous month, e.g. March flash rate divided by the February flash rate.

In the beginning of the fall season in Antarctica (March), the total number of flashes increased compared to the total number of flashes at the end of summer in Antarctica (February). This is shown clearly from the values of flash rate ratio between February and March 2017 for all observed storms (Storms region A, B and C). The total number of flashes keep increased in April for Storm region B. On the other hand, the total number of flashes for Storms region A and C started to decrease. For the rest of the months until June, the total number of flashes kept decreased drastically as evidenced from the large ratio values, e.g. a ratio of 61,357 from April to May for Storm region B. Interestingly, there is a slight increase for all storms during the winter season from June to July.

It seems that the results shown in Fig. 6 suggest that Storm region B produced significantly large amounts of CG flashes compared to Storms region A and C. For example, in March Storm region B produced more than 100,000 CG flashes when compared to Storm region A and C which both produced less than 20,000. It is important to realize here that Storm region B was located close to the LD sensor in Carlini Base (within 100 km) and therefore the detection efficiency is much higher than for Storms region A and C which were located between 500 and 800 km away from the LD sensor. So, it is logical that such large

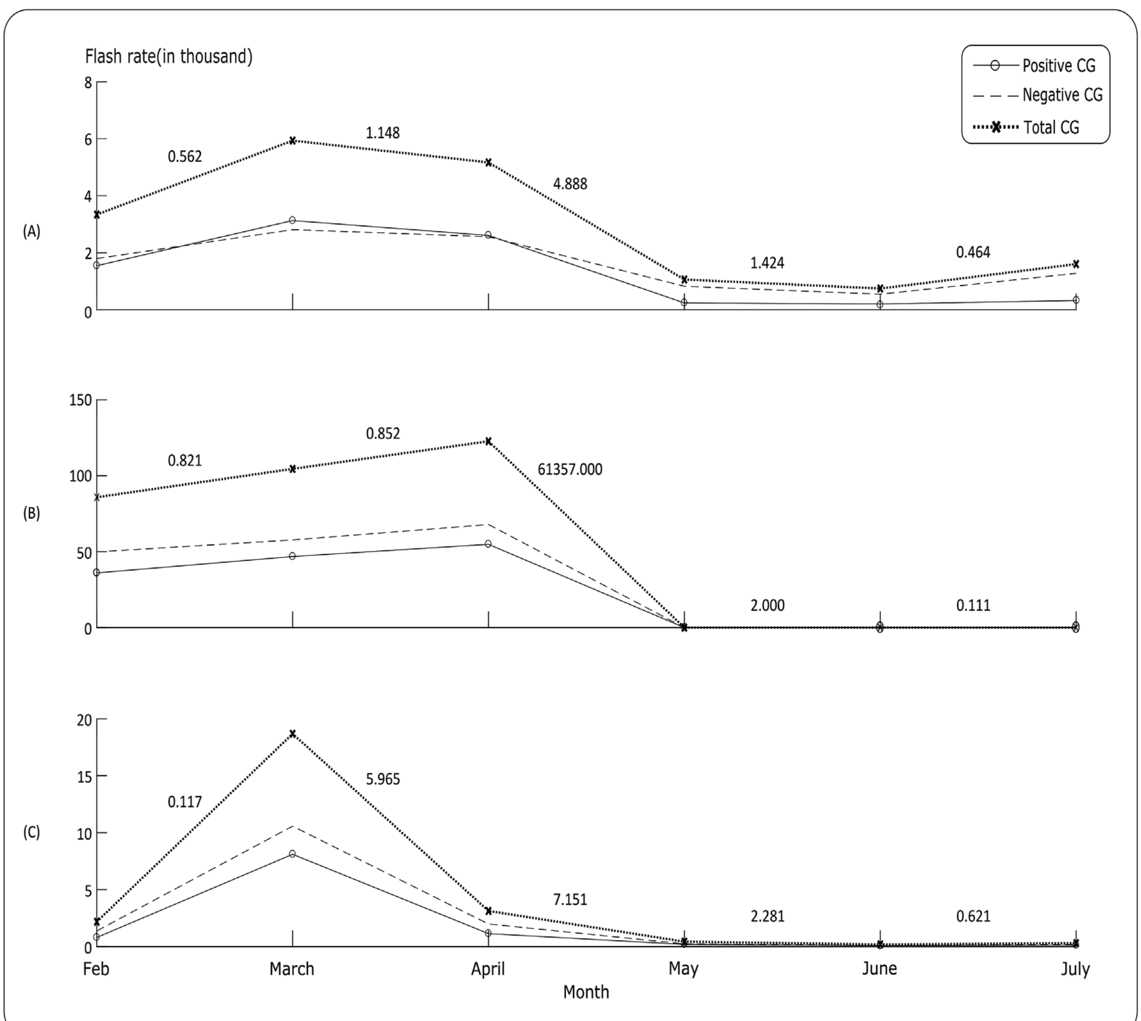

Fig. 6. Evolution of flash rate per month according to season from summer to winter (February to July 2017) for Storm region (A), Storm region (B) and Storm region (C).

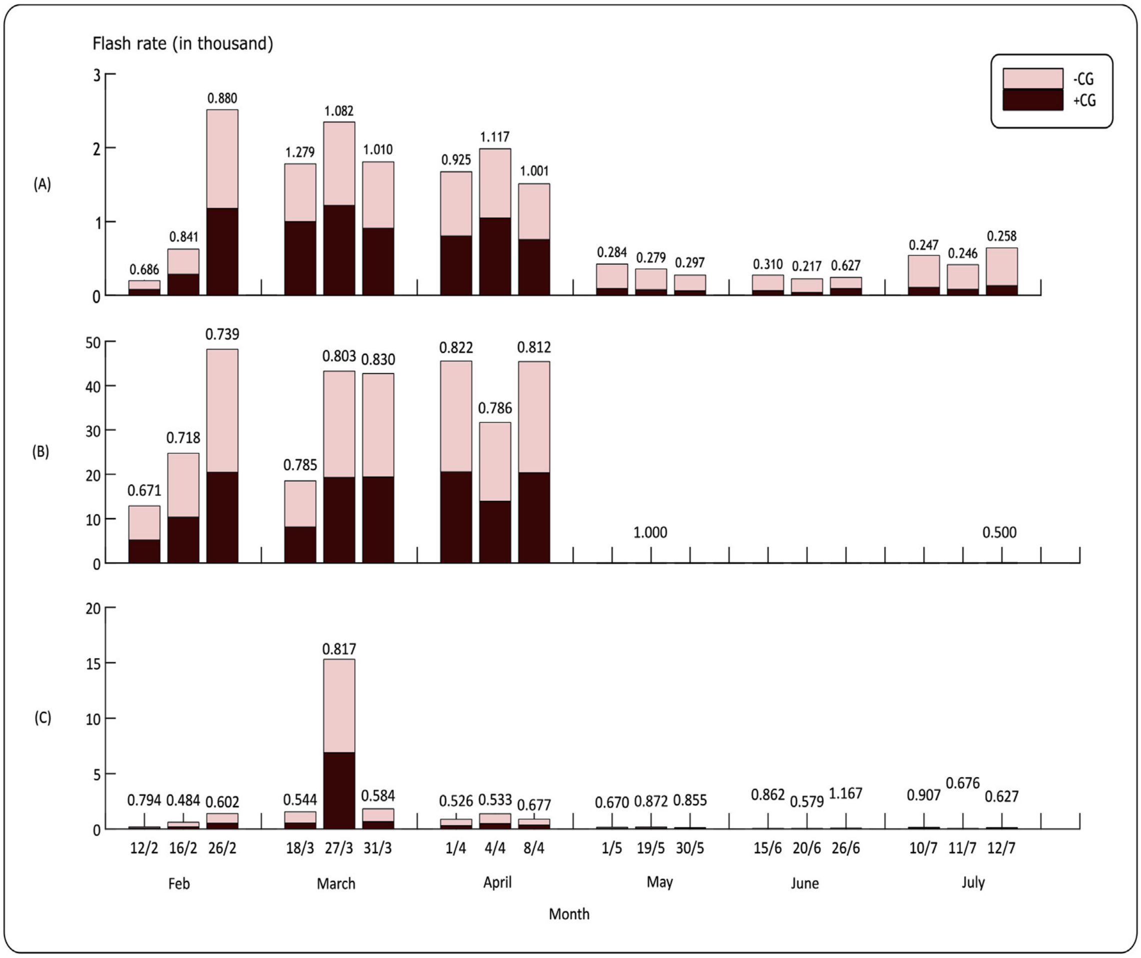

Fig. 7. Distribution of the flash rate per day for cloud to ground (CG) flashes for Storm region (A), Storm region (B) and Storm region (C).

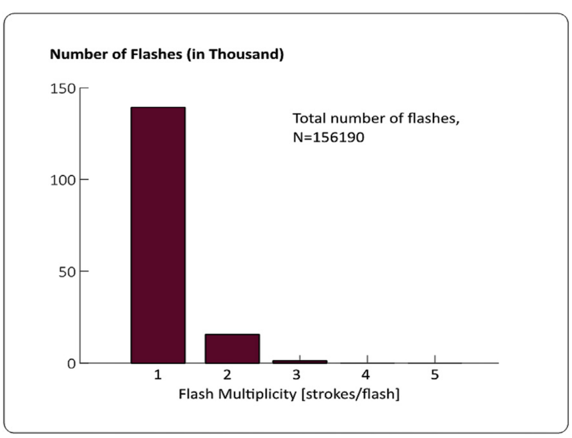

Fig. 8. Distribution of the number of strokes per flash for +CG flashes.

numbers of CG flashes were recorded for Storm region B. The important observation is that most of the CG flashes (both +CG and –CG) were produced during summer and fall while significantly smaller numbers of flashes were produced during winter. This result is expected because of the temperature dependence of the Clausius–Clapeyron relationship when the temperature is much warmer and humid during the summer and fall compared to the winter season. Moreover, we also anticipate that the occurrence of CG flashes in Antarctica must show similar characteristics to those produced in storms in high latitude regions (e.g. Scandinavian countries, Japan, etc.) with fewer winter storms.

Fig. 7 shows the distribution of the daily flash rate for +CG and –CG flashes. The values given on each bar are the ratio of +CG to –CG flashes. It seems that the distribution of daily flash rate is not uniform as some days produced fewer and some days produced more flashes. This in fact is related to the lifetime of the storms. Storms with shorter lifetimes produce less flashes and vice versa. The important analysis that we want to reveal is that the ratio of +CG to –CG flashes is relatively high when compared to the ratio obtained at other geographical

Table 2
Comparison of negative ground flashes with different flash multiplicity.

Researcher	Location	Number of flashes	Mean multiple stroke	Maximum multiple stroke
Present study (2019)	**Antarctica**	**199709**	**1.2**	**16**
Hazmi et al. (2016)	Indonesia	100	5.2	18
Baharudin et al. (2014)	Malaysia	100	4	14
Zhu et al. (2015)	Florida	478	4.6	17
Yair et al. (2014)	Israel	18611	1.4	16
Saba et al. (2010)	Brazil	233	3.8	16

regions. It is a well-known fact that the occurrence of +CG flashes is latitude dependent (Ahmad et al., 2015). In other words, tropical storms produce less +CG flashes when compared to high latitude storms.

Often in a tropical thunderstorm, the main positive charge centre is screened from the ground by the main negative charge centre and this pattern is influenced by the shape and size of the thunderstorm (with narrow, elevated mixed-phase regions, higher cloud tops, and slim shapes for hot tower thunderstorms). This in turn could explain why +CG flashes are very rare in the tropics (Ahmad et al., 2015). On the other hand, high latitude storms are generally thicker with lower cloud tops, e.g. around and less than 12 km for summer storms in Sweden. Therefore, the main positive charge centre is not screened from the ground and this in turn why +CG flashes are prevalent in high latitude storms (Rakov and Uman, 2003; Dwyer and Uman, 2014).

As expected, the results in Fig. 7 reveal that +CG flashes do occur in Antarctic storms, even for winter storms. The mean, median and range of the ratio of +CG to –CG flashes are 0.7, 0.718 and 0.217–1.279, respectively. In several thunderstorms, the number of +CG flashes even surpassed the total number of –CG flashes such as for Storm region A in March, Storm region B on May 19th, and Storm region C on June 26th. In total, the +CG flash count constituted 43.9% of the total flashes. Such prevalent occurrences of +CG flashes in Antarctica might be due very low cloud tops or perhaps the inversion of the dipole charge structure.

Table 1 provides a comparison on the number of strokes per flash for +CG flashes at various geographical locations and latitudes including the current results obtained from storms in Antarctica and Malaysia. The distribution of the numbers of strokes per flash from the Carlini Base for +CG flashes is depicted in Fig. 8.

Clearly, most of the +CG flashes (> 80%) have been recorded with only one or two strokes. As expected, the average multiplicity ranged between 1.1 and 1.5. The average multiplicity for our study in Antarctica is 1.1 and this value is consistent with some other studies carried out in tropical, subtropical and temperate (Sweden) regions. By making the comparison among the studies, the occurrence of five-stroke +CG flashes was the highest number of strokes found in this present study and four strokes are rarely reported (Johari et al., 2017; Baharudin et al., 2016; Heidler and Hopf, 1998). The multiple-stroke percentage found in this study was around 11% which is similar to recent results found by Johari et al. (2017) (12%) and comparable to the finding of Nag and Rakov (2012) (19%) and Saba et al. (2010) (19%). However, there is a big difference compared to the results obtained by Baharudin et al. (37%) and this may be due to the measurement period and the total number of samples taken in the observation. Heidler and Hopf (1998) and Heidler et al. (1998) found that different measurement periods had a significant effect to the value of the percentage.

Table 2 presents a comparison on the number of strokes per flash for –CG flashes at various geographical locations and latitudes including the current results obtained from storms in Antarctica. The average multiplicity and the maximum multiple stroke found in this study were 1.2 and 16 respectively. Both values are consistent with the results found by Yair et al. (2014) were 1.4 and 16 respectively. On the other hand, average multiplicity values found by other researchers (Hazmi et al., 2016; Baharudin et al., 2014; Zhu et al., 2015; Saba et al., 2010) were higher, perhaps because the number of samples taken were significantly smaller compared to the current study and Yair et al. (2014). This has a significant effect on the number of mean multiple strokes presented. Nevertheless, the maximum multiple strokes reported by Saba et al. (2010) were similar with the present study. Multiple-stroke positive flashes do occur, but they are relatively less common compared to multiple-stroke negative flashes as evidenced from Table 1 and also in Johari et al. (2017) and Rakov (2003). As presented in this study, the maximum number of strokes for +CG and –CG flashes from Antarctica thunderstorms were 5 and 16 respectively and these results are convincing when compared to the previous studies.

4. Conclusion

Characteristics of both +CG and –CG flashes have been analysed for 54 thunderstorms from February to July 2017 in area within 1,000 km of the Carlini Base station on the Antarctic Peninsula. The flash rate, flash multiplicity and the percentage of single-stroke flashes were examined for three different seasons – summer, fall and winter. The number of CG flashes found was 156,190 +CG and 199,709 –CG flashes comprising a total of 355,899 flashes. Most of the CG flashes (both +CG and –CG) were produced during the summer and fall while a significantly smaller number of flashes were produced during the winter. The percentages of CG flashes during the summer, fall and winter were 61.96%, 37.23% and 0.80% respectively. The majority of the +CG flashes (more than 80%) were single-stroke or two-stroke flashes. The average multiplicity was 1.1 and the maximum multiple strokes was five. The average multiplicity and the maximum multiple strokes found for –CG flashes were 1.2 and 16, respectively. The characteristics of both +CG and –CG flashes obtained in this study are fairly similar to other stroke counting studies in various geographical regions.

Acknowledgements

This research was funded by the Ministry of Science, Technology and Innovation Malaysia (MOSTI) through the Flagship Program under ZF-2014-016 grant. The authors would like to thank to Dr. Wayan Suparta and the Instituto Antartico Argentino (IAA) for the expedition to Antarctica at Carlini Base during the summer campaign 2016/2017, Universiti Teknikal Malaysia Melaka and the Ministry of Higher Education for their moral, operational and financial support throughout this PhD study. The authors wish to thank the World Wide Lightning Location Network (WWLLN) (http://wwlln.net), a collaboration among over 50 universities and institutions, for providing the lightning location data used in this paper. Participation of M. R. M. Esa is funded by UTM GUP Grants: 04G19 and 14J64. Participation of MR Ahmad is funded by UTeM Short Term Grant (PJP/2018/FKEKK/(3B)/S01615).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.polar.2019.05.002.

References

Abarca, S.F., Corbosiero, K.L., Galarneau Jr., T.J., 2010. An evaluation of the worldwide lightning location network (WWLLN) using the national lightning detection network (NLDN) as ground truth. J. Geophys. Res. 115, D18206. https://doi.org/10.1029/2009JD013411.

Adhikari, L., Wang, Z., Deng, M., 2012. Seasonal variations of Antarctic clouds observed by CloudSat and CALIPSO satellites. J. Geophys. Res. 117, D04202. https://dx.doi.org/10.1029/2011JD016719.

Ahmad, M.R., Esa, M.R.M., Cooray, V., Baharudin, Z.A., Hettiarachchi, P., 2015. Latitude dependence of narrow bipolar pulse emissions. J. Atmos. Sol. Terr. Phys. 128, 40–45.

Ahmad, M.R., Esa, M.R.M., Cooray, V., Dutkiewicz, E., 2014. Interference from cloud-to-ground and cloud flashes in wireless communication system. Electr. Power Syst. Res. 113, 237–246.

Akinyemi, M.L., Boyo, A.O., Emetere, M.E., Usikalu, M.R., Olawole, F.O., 2014. Lightning a fundamental of atmospheric electricity. IERI Procedia 9, 47–52.

Baharudin, Z.A., Cooray, V., Rahman, M., Hettiarachchi, P., Ahmad, N.A., 2016. On the characteristics of positive lightning ground flashes in Sweden. J. Atmos. Sol. Terr. Phys. 138–139, 106–111. https://doi.org/10.1016/j.jastp.2015.12.014.

Baharudin, Z.A., Noor Azlinda Ahmad, J.S., Mäkelä, Fernando, Mahendra, Cooray, Vernon, 2014. Negative cloud-to-ground lightning flashes in Malaysia. J. Atmos. Sol. Terr. Phys. 108, 61–67.

Boltek Corporation, 2000-2012. LD-350 Lightning Detector Installation/Operators Guide. Boltek Corporation, USA.

Boltek Corporation, 2004-2016. EFM-100 Atmospheric Electric Field Monitoring Installation/Operators Guide for Model EFM-100C. Boltek Corporation, USA.

Cooray, V., 2015. Mechanism of lightning flash. In: An Introd. To Light. Springer, Netherlands, pp. 91–116. https://doi.org/10.1007/978-94-017-8.

Dwyer, J.R., Uman, M.A., 2014. The physics of lightning. Phys. Rep. 534, 147–241.

Esa, M.R.M., Ahmad, M.R., Cooray, V., 2014. Wavelet analysis of the first electric field pulse of lightning flashes in Sweden. Atmos. Res. 138, 253–267 10.1016.j.atmosres.2013.11.019.

Fleenor, S.A., Biagi, C.J., Cummins, K.L., Krider, E.P., Shao, X., 2009. Characteristics of cloud- to-ground lightning in warm-season thunderstorms in the Central Great Plains. Atmos. Res. 91, 333–352. https://doi.org/10.1016/j.atmosres.2008.08.011.

Hazmi, A., Emeraldi, P., Hamid, M.I., Takagi, N., 2016. Some characteristics of multiple stroke negative cloud to ground lightning flashes in Padang. Int. J. Electr. Eng. Inf. 8 (2). https://doi.org/10.15676/ijeei.2016.8.2.14.

Heidler, F., Hopf, C., 1998. Measurement results of the electric fields in cloud-to-ground lightning in nearby Munich, Germany. IEEE Trans. Electromagn Compat 40-436–443. https://doi.org/10.1109/15.736204.

Heidler, F., Drumm, F., Hopf, C., 1998. Electric fields of positive earth flashes in near thunderstorms. Int. Conf. Light. Prot. 42–47.

Hutchins, M.L., Holzworth, R.H., Rodger, C.J., Brundell, J.B., 2012. Far field power of lightning strokes as measured by the world wide lightning location network. J. Atmos. Ocean. Technol. 29, 1102–1110.

Johari, D., Cooray, V., Rahman, M., Hettiarachchi, P., Ismail, M.M., 2017. Features of the first and the subsequent return strokes in positive ground flashes based on electric field measurements. Electr. Power Syst. Res. 150–55, 62. https://doi.org/10.1016/j.epsr.2017.04.031.

Nag, A., Rakov, V.A., 2012. Positive lightning: an overview, new observations, and inferences. J. Geophys. Res. 117, D08109. 2012. https://doi.org/10.1029/2012JD017545.

Qie, X., Zhang, Y., Zhang, Q., 2006. Characteristics of lightning discharges and electric structure of thunderstorm. Acta Meteorol. Sin. 20.

Rakov, V.A., 2003. A review of positive and bipolar lightning discharges. Bull. Am. Meteorol. Soc 84-767–776. https://doi.org/10.1175/BAMS-84-6-767.

Rakov, V.A., Uman, M.A., 2003. Lightning: Physics and Effects. Cambridge University Press.

Rodger, C.J., Brundell, J.B., Holzworth, R.H., Lay, E.H., Crosby, N.B., Huang, T.Y., Rycroft, M.J., 2009. April. Growing detection efficiency of the world wide lightning location network. AIP Conf. Proc 1118 (118), 15–20.

Rodger, C.J., James, B.B., Holzworth, R.H., Emma, D., Stan, H., 2017. The World Wide Lightning Location Network (WWLLN): Update on New Dataset and Improved Detection Efficiencies. URSI GASS, Montreal, pp. 19–26 August 2017.

Rudlosky, S.D., Shea, D.T., 2013. Evaluating WWLLN performance relative to TRMM/LIS. Geophys. Res. Lett. 40, 2344–2348. https://doi.org/10.1002/grl.50428.

Saba, M.M.F., Ballarotti, M.G., Pinto Jr., O., 2006. Negative cloud-to-ground lightning properties from high speed video observations. J. Geophys. Res. 111, D03101. https://doi.org/10.1029/2005JD006415.

Saba, M.M.F., Schulz, W., Warner, T.A., Campos, L.Z.S., Schumann, C., Krider, E.P., Cummins, K.L., Orville, R.E., 2010. High speed video observations of positive lightning flashes to ground. J. Geophys. Res. 115, D24201. https://doi.org/10.1029/2010JD014330.

Yair, Y., Shalev, S., Erlich, Z., Agrachov, A., Katz, E., Saaroni, H., Price, C., Ziv, B., 2014. Lightning flash multiplicity in eastern Mediterranen thunderstorms. Nat. Hazards Earth Syst. Sci. 14, 165–173.

Zhang, H., Lu, G., Qie, X., Jiang, R., Fan, Y., Tian, Y., Sun, Z., Liu, M., Wang, Z., Liu, D., Feng, G., 2016. Locating narrow bipolar events with single-station measurement of low- frequency magnetic fields. J. Atmos. Sol. Terr. Phys. 143–144, 88–101.

Zhu, Y., Rakov, V.A., Mallick, S., Tran, M.D., 2015. Characterization of negative cloud-to-ground lightning in Florida. J. Atmos. Sol. Terr. Phys. 136 (Part A), 8–15. https://doi.org/10.1016/j.jastp.2015.08.006.

Zikri, M., Sidik, M.A.B., Ahmad, M.R., Sabri, M.H.M., Perianan, D., Esa, M.R.M., Malek, Z.A., Lu, G., Zhang, H., 2018. Evaluation of the existence of initial breakdown process for cloud- to-ground flashes. In: 2018 International Conference on Electrical Engineering and Computer Science (ICECOS). PANGKAL PINANG, Indonesia, pp. 425–428. https://doi.org/10.1109/ICECOS.2018.8605182.