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# Lightning flash multiplicity in Eastern Mediterranean thunderstorms

**Y. Yair[1], S. Shalev[2], Z. Erlich[3], A. Agrachov[4], E. Katz[5], H. Saaroni[2], C. Price[4], and B. Ziv[1]**

[1]Department of Life and Natural Sciences, The Open University of Israel, 1 University Road, P.O. Box 808, Ra’anana, 43537, Israel
[2]Department of Geography and the Human Environment, Tel-Aviv University, Ramat Aviv, Tel-Aviv, 69978, Israel
[3]Department of Math and Computer Science, The Open University of Israel, Ra’anana, 43537, Israel
[4]Department of Geophysical, Atmospheric and Planetary Sciences, Tel-Aviv University, Ramat Aviv, Tel-Aviv, 69978, Israel
[5]Israel Electric Corporation, Research Laboratories, Haifa, Israel

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Correspondence to: Y. Yair (yoavya@openu.ac.il, yoavyair@gmail.com)

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## Abstract

Cloud-to-ground lightning flashes usually consist of one or several strokes coming in very short temporal succession and close spatial proximity. The common method for converting stroke data into flashes is using the National Lightning Detection Network (NALDN) thresholds of maximum temporal separation of 0.5 s and maximum lateral distance of 10 km radius between successive strokes. In the present study, we tested a location-based algorithm with several spatial and temporal ranges, and analyzed stroke data obtained by the Israel Lightning Location System (ILLS) during one year (1 August 2009–31 July 2010). We computed the multiplicity, the percentage of single stroke flashes and the geographical distribution of single vs. multiple-stroke flashes for thunderstorms in the Eastern Mediterranean region. Results show that for the NALDN thresholds, the percentage of single stroke flashes in Israel was 37 % and the average multiplicity was 1.7. We re-analyzed the data with a spatial range that equals twice the ILLS location error and shorter times. For the new thresholds of maximum distance of 2.5 km and maximum allowed temporal separation of 0.2 s we find that the mean multiplicity of negative CGs is lowered to 1.4 and find a percentage of 58 % of single stroke flashes. A unique severe storm from 30 October 2009 is analyzed and compared to the annual average of 2009/10, showing that large deviations from the mean values can occur in specific events.

## 1 Introduction

An important characteristic of lightning is the number of strokes per flash. Different lightning location systems use different methods to group strokes into flashes and to determine the flash count and multiplicity from the stroke data, thus affecting the resultant values. As most lightning studies refer to flashes and not strokes, and as different algorithms are used to group strokes into flashes, the consistency of lightning characteristics derived from different systems may be impaired. In the US, before the

1994–1995 NLDN upgrade (Cummins et al., 1998a), the number of strokes in a flash was defined as the maximum number of strokes observed by any responding direction-finding station within 2.5° and one second of the first stroke. In the upgraded NLDN, strokes are assigned to a given flash if they occur within 10 km of the first stroke and within a time interval of 500 ms from the previous stroke, and the maximum flash duration still being one second. In addition, in the upgraded NLDN, a stroke is included in a flash if it is located within 10–50 km of the first stroke and if the location error ellipses of these two strokes overlap (Rakov and Huffins, 2003). Defer et al. (2005) studied winter lightning activity in the Eastern Mediterranean, using data from the UK Met Office VLF sferics arrival time (ATD) system. They used the criteria employed by the NLDN mentioned above (e.g. 10 km and 500 ms). Based on 20 lightning days with 266 000 "fixes" (a "fix" is the ATD term for a CG ground location equivalent to a stroke), they concluded that 85 % of CG flashes are composed of a single stroke. The multiplicity was found to range between 1 and 10 with an average value of 1.2 fixes per flash.

Cummins et al. (1998a) mention that the average multiplicity was generally thought to be between 3 and 4, as found by Thomson et al. (1984). The multiplicity determined by the NLDN according to the two different methods (before and after the upgrade) for two years after the upgrade were different. The result obtained using the new method was lower (1.9) than the result obtained for the same database by the previous method (2.7). Orville et al. (2002) analyzed three years of data from the NALDN and found that in most regions the mean negative multiplicity was lower than 2.6. Two important insights emerge: (a) in general, multiplicity increases with higher negative peak currents (first stroke peak current) and (b) the high mean multiplicity found in certain regions (e.g. southeastern states) may be an artifact of the network's enhanced sensitivity to subsequent strokes, due to the close spacing of lightning sensors in that region. Analyzing 10 yr of lightning data from the NLDN (1989–1998), Orville and Huffins (2001) found that the negative multiplicity is slightly above 2.5 for the period 1989–1994, subsequently decreasing to slightly over 2.0 during the period 1995–1998.

They attribute the results to the multiplicity algorithm change in 1994. Rakov and Huffins (2003) summarize different studies from Florida, New Mexico, Sri Lanka and Sweden, all of which found that the majority of negative flashes contain more than one stroke and that less than 20 % are single-stroke flashes. The mean negative multiplicity reported by Orville et al. (2010) for the years 2001–2009 ranges between 2.2 and 2.6. The multiplicity values are affected by improved detection ability as a result of some upgrades to the NALDN, which consist of 200 sensors (in 2010). For example a higher negative multiplicity was reported for 2002 compared to 2001 and a 30 % increase in positive multiplicity from 2001 to 2004, following the 2002–2003 upgrade. The mean multiplicity for the Austrian Lightning Detection and Information System (ALDIS) was 2.21 and for the FM-System $m = 2.29$ (Schulz and Diendorfer, 2006). In Brazil, the average multiplicity of negative CG flashes reported by BrasilDat was 1.9, but may have been an underestimation due to the low stroke detection efficiency of the network at that period of time (Pinto et al., 1999).

In Israel, the percentage of negative single-stroke flashes reported by ILLS for the period 2000–2007 was 38.5 % (Katz and Kalman, 2009). These results were based on the updated NLDN algorithm, which used thresholds of 0.5 s and 10 km. The mean value of the multiplicity was found to be 2.7 (this value was obtained by using a different averaging method which excludes flashes with only one stroke).

Do multiple strokes of a single cloud-to-ground (CG) flash indeed hit the same physical location, in terms of geographical coordinates? If this would be the case, it would seem logical that the algorithm for grouping strokes into a flash should consider strokes to be part of the same flash only if they successively hit at a distance equal to twice the location accuracy of that location system, within the predetermined time range. When keeping the temporal clustering criteria the same, two strokes within a distance less than twice the location uncertainty are then grouped in a single flash. The typical location accuracy achieved by the NLDN following the 1994 upgrade (as a result of the 106 sensors located over the continental US in 1996) was 500 m (Cummins et al., 1998a). If multiple strokes indeed hit the same location, and if the median accuracy is 500 m, then the maximum spatial range for grouping two strokes into one flash should be 1 km. However, the NLDN, as part of the 1994 upgrade, adopted a new method for grouping individual strokes into one flash, using a spatial range of 10 km. Rakov and Huffins (2003) explained that in some optical studies of flash multiplicity, the occurrence of a new path between the cloud base and the ground was treated as the beginning of a new flash, regardless of the time elapsing from the preceding stroke and the likelihood of a common channel section inside the cloud. In their view, this approach separates a single multi-grounded lightning discharge inappropriately into two or more flashes with one ground termination each.

A rigorous approach to the issue of flash multiplicity is based on the usage of video cameras, attempting to record all strokes in a given flash while comparing to the detection of the same flash by regular electromagnetic methods. Such "video multiplicity" is often hard to achieve due to obscuration of the lightning ground termination point by clouds and precipitation, and its accuracy depends on the frame-rate of the camera (Saraiva et al., 2010). Nevertheless, several successful studies have been conducted in recent years, aided by advances in imaging technology. Thottappillil et al. (1992) used a TV camera network and found that the distance between multiple strokes of 22 flashes, ranged from 0.3 to 7.3 km, with a mean of 1.7 km. For 39 negative CG flashes that were recorded on video in Arizona (Stall et al., 2009), the mean and standard deviation of the distance between the strike point of the first stroke and those of the subsequent strokes was found to be 2.3 ± 1.7 km. Similar work conducted by Fleenor et al. (2009) in warm season thunderstorms in the Great Plains in the US. In Brazil, Saba et al. (2010) studied 103 +CG flashes that were recorded using high speed video cameras, of which 20 had multiple strokes. For the multiple stroke positive flashes, where each stroke was located by a Lightning Location System (LLS), they were able to estimate the horizontal distances between the different ground strike points. These distances ranged from 2 to 53 km, while most (70 %) were greater than 10 km, the default range used by the NLDN. In addition, they found (Saba et al., 2010) an inter-stroke time interval of 94 ms for +CG, which is about 1.5 times greater than the average inter-stroke interval in negative CG flashes (60 ms). Using a time limit of 500 ms, as used by the NLDN, provides a higher reliability in the resulting flash data but may have erroneously lowered the total number of flashes. Ballarotti et al. (2012) conducted an accurate stroke-count study using high-speed cameras (at 1000–8000 frames per second). They suggested using the new term $N_{\mathrm{STF}}$ to describe the ratio between the average number of strokes per flash and the average number of ground contacts per flash. Based on their data of 833 negative CGs (out of 4041 strokes), the multiplicity was 4.6 and the number of ground points per flash 1.7, resulting in $N_{\mathrm{STF}} = 4.6/1.7 = 2.7$. The percentage of single stroke flashes was found to be 17 %.

The described differences in temporal and spatial thresholds between consecutive strokes used by various Lightning Location Systems and researchers impair establishing common databases and accurate flash density maps, and necessitate using realistic values. The present study aims to evaluate how the multiplicity and the stroke-to-flash ratio change when alternative parameters are used, and to suggest new thresholds for future studies of flash multiplicity.

## 2 Data

In the present study we used stroke data for the period 1 August 2009–31 July 2010 (later referred as year 2009/10) obtained by the Israel Lightning Location System (ILLS) operated by the Israel Electric Corporation (IEC). The ILLS during that period consisted of 8 sensors: 5 Lightning Position and Tracking System (LPATS), 2 IMProved Accuracy from Combined Technology (IMPACT) and one lightning sensor of type LS7000. Over the land area of Israel, where all 8 sensors are located, the stroke detection efficiency is > 80 %, and it decreases with distance from the network center (Fig. 1). The flash detection efficiency is assumed to be more than 90 % above Israel's central areas, though the accurate value is unknown. The median semi-major axis length of the 50 % statistical confidence area for locating the ground strike point in the abovementioned region is 1.3 km. The total area investigated in the present research covers Israel and its neighboring region and is ~ 500 000 km$^2$, of which 40 % are over the Mediterranean Sea. The spatio-temporal distribution of lightning over Israel and the neighboring area and a detailed description of the research methodology are described in Shalev et al. (2011).

## 3 Methodology and results

Based on the fact that the average time interval between successive return strokes in any flash is usually several tens of milliseconds, a value of 0.2 s may better represent the real multiplicity compared with the nominal 0.5 s. Similarly, most video-based studies of lightning strike locations show a mean range of less than 2.5 km between two ground terminations of the same flash, and so a spatial range of 10 km seems to be too large and can potentially misclassify independent flashes as subsequent strokes of a single flash. Such broad clustering criteria may eventually lead to reporting lower values of flash density than occur in reality.

In order to evaluate the sensitivity of the multiplicity values to the chosen thresholds, we used different criteria from those commonly used by operational lightning detection networks. For computing the multiplicity of cloud-to-ground flashes in winter thunderstorms in Israel, we tested a revised location-based algorithm in order to group different successive strokes into a single flash: (a) inter-stroke time interval < 0.2 s, (b) location distance within 2.5 km and (c) no restriction on the maximum flash duration. The distance in kilometers between strokes was computed from the longitude and latitude reported by the ILLS, converted to radians using the spherical Law of Cosines formula, based on a spherical earth assumption (ignoring the ellipsoidal effect).

$$d = \mathrm{acos}(\sin(\mathrm{lat1}) \cdot \sin(\mathrm{lat2}) + \cos(\mathrm{lat1}) \cdot \cos(\mathrm{lat2}) \cdot \cos(\mathrm{long2} - \mathrm{long1})) \cdot R \qquad (1)$$

where $d$ is the computed distance between two strokes, lat1, long1 and lat2, long2 are the location values of the two strokes being examined and $R$ is the earth's radius. A Visual Basic application was developed that can also be used for further studies.

### 3.1 Lightning parameters with NALDN criteria

Figure 1 shows the multiplicity distribution of $N = 10\,754$ negative CG flashes above Israel when using the NALDN parameters for grouping strokes into flashes (10 km, 0.5 s). The mean negative multiplicity was 1.73, with a long tail of higher values, with a maximum of 16 strokes in a single flash. The highest probability (64 %) is for single-stroke flashes, with 19 % having two strokes, 9 % having 3 strokes and much lower percentages with higher multiplicity values. The distribution is markedly different than reported in accurate stroke count studies in Brazil (Saba et al., 2006) and Arizona (Saraiava et al., 2010), where the average multiplicity was 3.9. Fleenor et al. (2009) studied storms in the US mid-planes and reported a video multiplicity average of 2.83 with median 2.00 for 103 strokes. The percentage of single-stroke flashes reported by the NALDN is a factor of 2–3 higher than from the accurate-stroke-count studies in Florida and is a factor of 3–4 higher in New Mexico. The ILLS results for 2009/10 are more similar to the distribution found by the NALDN for these same regions.

The distributions in Fig. 2a and b reflect the inter-stroke characteristic found for the study period. Here $N$ is the number of subsequent strokes. The mean inter-stroke distance between consecutive strokes is 2.24 km and the mean inter-stroke interval is 93 ms. These results are in good agreement with the results of Stall et al. (2009) who found a mean inter-stroke distance of 2.6 km and a mean inter-stroke interval of 98 ms for strokes which used preexisting channel and 84 ms for strokes which created new ground contacts. It is also similar to the results of Saba et al. (2010) who found a geometric mean value of 61 ms between successive strokes in a given flash. Ballarotti et al. (2012) reported an interstroke geometric mean of 64 ms, based on 3147 strokes. These studies support the validity of using a shorter temporal threshold for determining the stroke-flash conversion ratio.

### 3.2 Mean multiplicity using different grouping criteria

The average multiplicity was re-calculated for time differences of 0.2 and 0.5 s and for distances of 2.5, 5, 10 km between successive strokes (Fig. 3). Table 1 is reproduced from Rakov and Huffins (2003) with addition of our results for the annual lightning data of 2009/10 for the full ILLS coverage area (later referred to as “entire region”) and specifically for the land area of Israel, where a better location accuracy is stated. For the entire region, the average negative multiplicity is 1.6 based on the NALDN thresholds (10 km and 0.5 s). When excluding single-stroke flashes the multiplicity was found to be $m = 2.9$. This calculation was performed in order to enable comparison to the value of 2.7 computed by Katz and Kalman (2009), who discounted single-stroke flashes from their statistics. We find that the percentage of single-stroke flashes changes dramatically from 42 % to 71 % when using different range thresholds. We also computed the values based on the data gathered from the entire region by the ILLS, which obviously includes regions were the detection efficiency as well as the location accuracy are lower. These regions are expected to experience lower values of multiplicity, similar to the findings of Orville et al. (2010) who presented multiplicity maps for North America. For the land area of Israel, where detection efficiency is > 90 % and the median location accuracy is better than 1.3 km (Katz and Kalman, 2009), the mean negative multiplicity was found to be 1.73 for the NALDN thresholds, and 1.2 when using stricter ranges of 0.2 s and 2.5 km. Both values are lower than the values obtained for the entire region.

The geographical distributions of the mean negative multiplicities for two different sets of thresholds are shown in Fig. 4. We show multiplicity distribution map for the NALDN thresholds of 10 km, 0.5 s (Fig. 4a) and for 2.5 km and 0.2 s (Fig. 4b). The cell size for grouping lightning densities in both maps is 10 km$^2$. For the regular ranges (Fig. 4a), the highest multiplicity of values in the range of 2.4–6 strokes per flash are seen above the Mediterranean Sea close to the coastline. In contrast, values exceeding 1.5 are very rare for the stricter thresholds (Fig. 4b). In this case values of 1.5 to 1.8

can be seen above the Mediterranean Sea and above Israel. In both maps, low values are seen at the borders of the ILLS detection range and along the Jordan valley and its continuation southward towards the Red Sea. It is somewhat surprising that the multiplicity is higher over the sea, since one would expect the land area to have better contact points to the approaching stepped leader.

### 3.3 Number of ground contact points

It is a known fact that the number of contact points changes with the number of strokes. Valine and Krider (2002) imaged 386 CGs and found 558 different strike points, leading to an average number of 1.45 ground terminations per CG flash (their Fig. 7). Fleenor et al. (2009) reported a mean value of 1.56 contact points per flash, based on video studies of 103 flashes. Saraiava et al. (2010, Fig. 12) gave 1.7 contact points per flash based on 344 flashes. Analysis of flashes with the highest number of strokes in our data shows that although there is large spread in interstroke distance (as evident in Fig. 2b), high multiplicity strokes have contact points that are distributed with an inter-stroke distance usually less than 2 km. Three such events (named E1, E2 and E3) are shown in Fig. 5a–c. Event E1 from the 18 January 2010 at 13:41 GMT had the highest number of strokes: 17. Event E2 from the 26 February 2010 at 15:50 GMT includes 15 strokes and event E3 from the 7 December 2009 at 11:55 GMT includes 13 strokes. The numbers in Fig. 5 indicate the stroke order in the flash and the circle size is proportional to the stroke peak current as measured by the ILLS. Obviously the first return stroke does not always exhibit the highest peak current. Similar to results reported by Fleenor et al. (2009, Fig. 5). It may be possible that strokes 1, 2 and 8 of event E1 and strokes 1 and 10 of event E3 are part of a separate flash. These values fall within 2.5 km indicating a very tight grouping of consecutive strokes in high multiplicity flashes.

### 3.4 The storm of 30 October 2009

During 30 October 2009, a severe storm occurred over the Eastern Mediterranean and gradually drifted from the west toward the Israeli coastline. This storm was associated with a well developed Cyprus low, accompanied by an upper-level trough, a combination shown to favor intense thunderstorms over the Levant (Ziv et al., 2009). During 20 h starting at 04:00 UT, the ILLS registered a total of 20 696 strokes, of which 19 728 were negative cloud to ground flashes (95.32 %), 943 were positive (4.55 %) and 25 bi-polar (0.012 %). Figure 6a shows the land/sea distribution of strokes: it is evident that most lightning activity takes place above the Mediterranean Sea or within the coastal region, defined as 10 km from land. A similar pattern was reported by Altaratz et al. (2001) indicating that lightning occurs mostly over the relatively warm water of the Mediterranean Sea where instability and humidity fluxes offer favorable conditions for convection and electrification. Figure 6b shows the temporal distribution of flashes along the day. When applying the regular criteria for grouping the strokes into flashes, the results for negative CGs show a multiplicity of 2.06 when considering all flashes, and 3.25 when excluding single-stroke flashes. For these thresholds the maximum multiplicity is $m = 17$. When using tighter thresholds (0.2 s and 1 km) the multiplicity for all flashes drops to 1.15 and without single-stroke flashes is only 2.41, and the maximum is $m = 11$. Intermediate values of 0.2 s and 10 km show that for all strokes the average multiplicity is 1.83, and without single stroke flashes it is 3.03. These changes reflect the sensitivity the computed multiplicity values to the chosen thresholds and the fact that occasional events may deviate significantly from the annual average values. Figure 7 shows the distribution of the peak current (Ip) for single-stroke flashes and for higher values of multiplicity. Clearly, single-stroke flashes show a wider distribution of peak-currents, while multiple strokes show narrower distributions. Interestingly, the last strokes of flashes with $m > 2$ converges to a common values of 14 kA. Similar distribution of peak current is found by Fleenor et al. (2009), with a mean value of 23.3 kA for the first stroke.

## 4 Conclusions

The mean multiplicity found for the stroke data over Israel recorded in the year 2009/10 using the general algorithm, including single-stroke flashes is 1.73. This value is lower than what is reported in other studies. The only other multiplicity value for Israel which can be used for comparison is the one computed by the IEC for the years 2000–2007 (Katz and Kalman, 2009). That value computed is taking in account only flashes with two or more strokes ($m \geq 2$). The multiplicity for flashes with $m \leq 2$ was also computed by Schultz and Diendorfer (2006) in order to overcome the differences between the Austrian Lightning Detection and Information System (ALDIS) and the data from the FM-System field measurement. The result was almost identical with 4.1 strokes per flash. In Israel, the result for 2000–2007, excluding single stroke flashes computed by Katz and Kalman (2009) was 2.7, similar to the 3.0 computed in the present study for the 2009/10 season.

In this study, we computed the mean multiplicity and percentage of single stroke flashes for negative cloud-to-ground flashes using an algorithm based on the spatial accuracy of the ILLS. The algorithm examined all strokes within a 2.5 km radius (twice the ILLS accuracy) from the location of the first stroke and difference temporal duration of 0.2 s. The multiplicity in Israel, where flash detection efficiency is > 90 % and location accuracy is better than 1.3 km, was found to be 1.4. We also computed the negative multiplicity for wider ranges and for the NALDN thresholds of 10 km and 0.5 s. The result for Israel was 1.7. Both values are lower than reported in most lightning climatology studies around the world (and see Table 1). This may be explained by the dominance of winter thunderstorms in the Eastern Mediterranean, which have different characteristics than summer or tropical convective storms, that are most studied globally (Cummins et al., 1998b; Schulz et al., 2005).

We believe that the temporal threshold of 0.5 s between successive strokes may be too large since the average inter-stroke interval in CG flashes was found to be 60 ms in negative flashes and 94 ms in positive flashes (Saba et al., 2010). We consider a safe margin of more than twice the average inter-stroke interval and recommend using a maximum temporal range of 0.2 s (200 ms) between successive strokes. Similarly, a maximum spatial range of 10 km is too large and may misclassify independent flashes as subsequent strokes of a single flash: most video-based studies show a separation range of less than 2.5 km between two ground termination points of the same flash. We therefore recommend a spatial range of twice the stated average accuracy of the lightning location system. This may lead to some multi-grounded flashes being misclassified as separate flashes, but will make the entire flash data more reliable. Indeed, Valine and Krider (2002) showed that 35 % of video-recorded cloud-to-ground flashes strike in two or more places separated by tens of meters or more. Such separation falls within most lightning location systems' accuracy and so our suggested threshold seems to be reasonable.

The estimated multiplicity of flashes is affected not only by the detection efficiency of the system, but also by the algorithm that groups strokes into flashes. Hence, it is somewhat difficult to compare published lightning climatologies – such as flash densities – from ground-based networks and satellite data or to accurately conclude that lightning characteristics vary between different regions and climates without a common, standard, agreed upon, benchmark. It is highly recommended that stroke data together with the thresholds used for computing flash data will become an essential part of future lightning climatology studies. This would lead to a better basis for comparison between the different regional and global data-sets. Moreover, the multiplicity of flashes, together with the algorithm used for computing flashes out of the stroke data, are vital for any lightning climatology analysis aiming to monitor changes in global lightning patterns in view of future climate changes (Price, 2009).

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**Table 1.** Average multiplicity, maximum multiplicity and percentage of single-stroke flashes based on data from different lightning detection networks. Reproduced from Rakov and Huffins (2003).

| Reference | Geographical region | | Observation period | # negative flashes | Avg mul. | Max mul. | % of single-stroke flashes |
|---|---|---|---|---|---|---|---|
| Diendorfer et al. (1998) | Austria | | 1996 | 46 420 | 2.7 | 15 | 40 |
| Rakov and Huffins (2003) | Florida | | 1995–2001 | 18 997 390 | 2.4 | 15 | 44 |
| | New Mexico | | 1995–2001 | 10 789 675 | 2.1 | 15 | 51 |
| | Contiguous US | | 1995–2001 | 165 074 265 | 2.2 | 15 | 49 |
| This study | E. Med | (0.5 s, 10 km) | 2009–2010 | 231 347 | 1.6 | 17 | 42 |
| | | (0.5 s, 5 km) | | | 1.4 | 17 | 52 |
| | | (0.5 s, 2.5 km) | | | 1.3 | 16 | 67 |
| | | (0.2 s, 2.5 km) | | | 1.2 | 16 | 71 |
| | Israel | (0.5 s, 10 km) | 2009–2010 | 18 611 | 1.7 | 17 | 37 |
| | | (0.5 s, 5 km) | | | 1.6 | 16 | 42 |
| | | (0.5 s, 2.5 km) | | | 1.5 | 16 | 52 |
| | | (0.2 s, 2.5 km) | | | 1.4 | 16 | 58 |

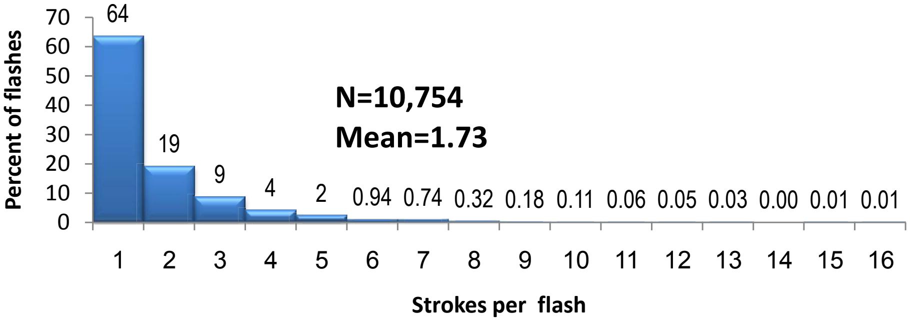

**Fig. 1.** The multiplicity distribution in winter thunderstorms in the study area.

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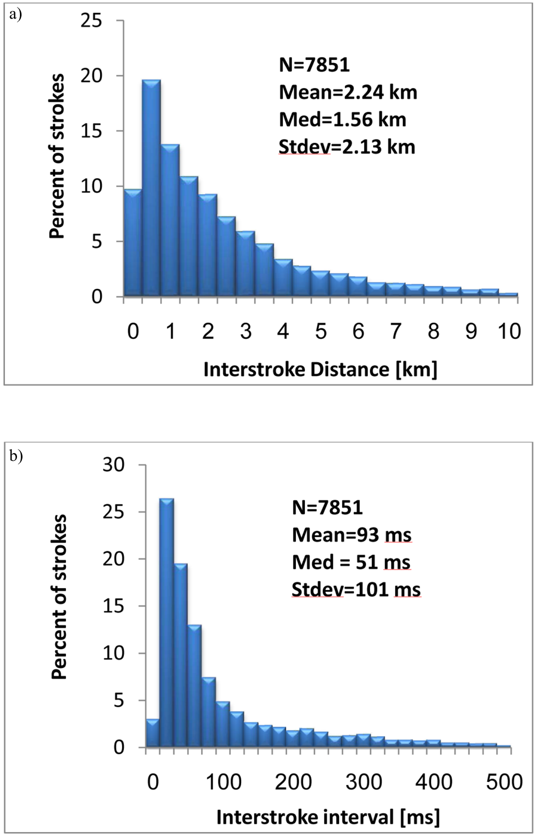

**Fig. 2. (a)** Distribution of inter-stroke distances in km. **(b)** Distribution of the interstroke time interval in ms.

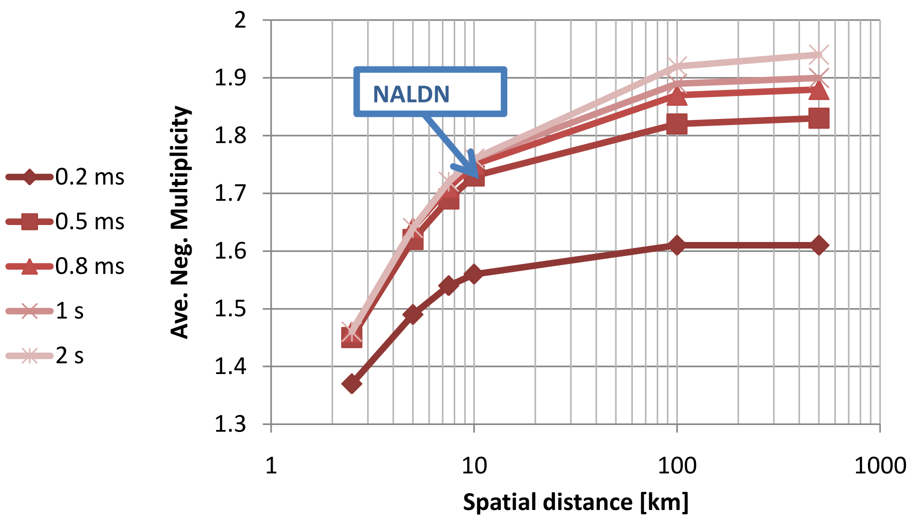

**Fig. 3.** Average negative multiplicity as a function of the time interval.

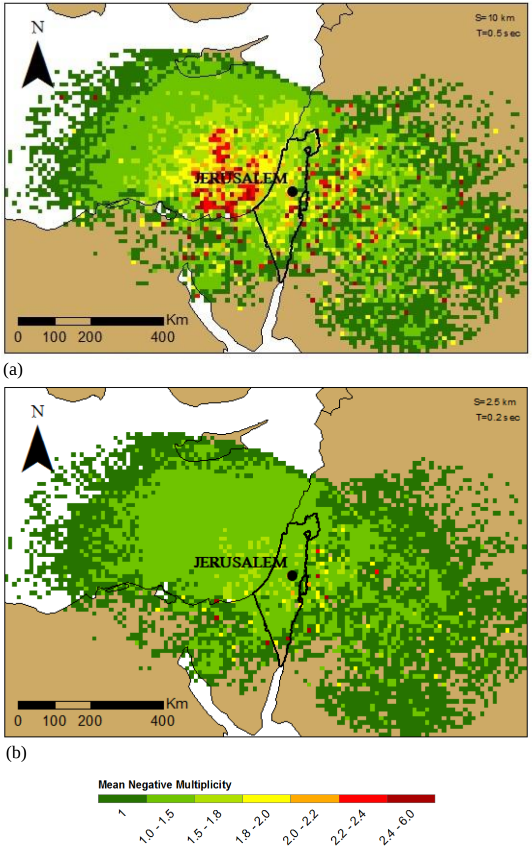

**Fig. 4. (a)** The negative ground flash multiplicity for thresholds of 0.5 s and 10 km. **(b)** The negative ground flash multiplicity for thresholds of 0.2 s and 2.5 km.

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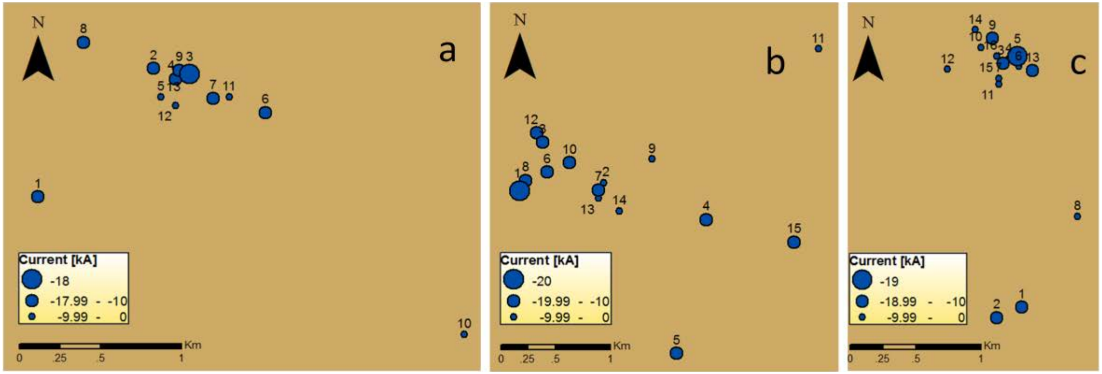

**Fig. 5.** Spatial distribution of succeessive strokes in 3 different lightning events with high multiplicity values.

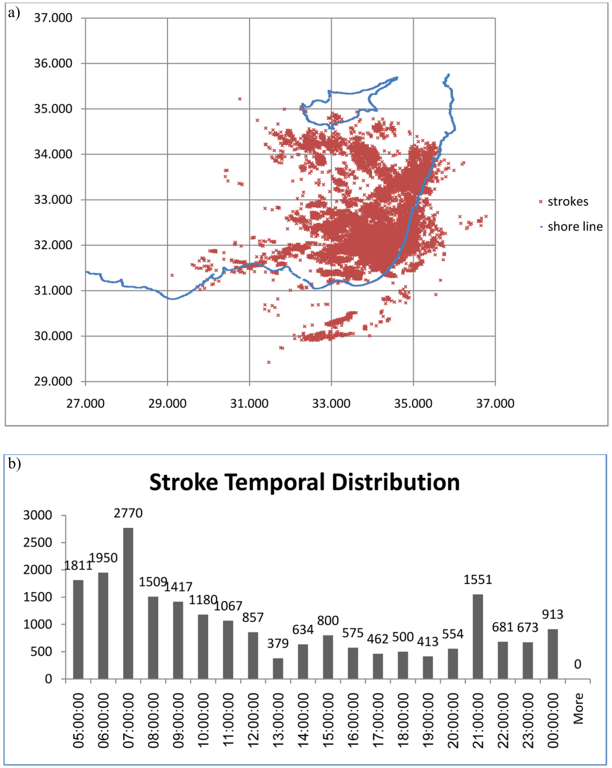

**Fig. 6. (a)** The distribution of strokes for the storm of 30 October 2009. **(b)** The temporal distribution of strokes along the day.

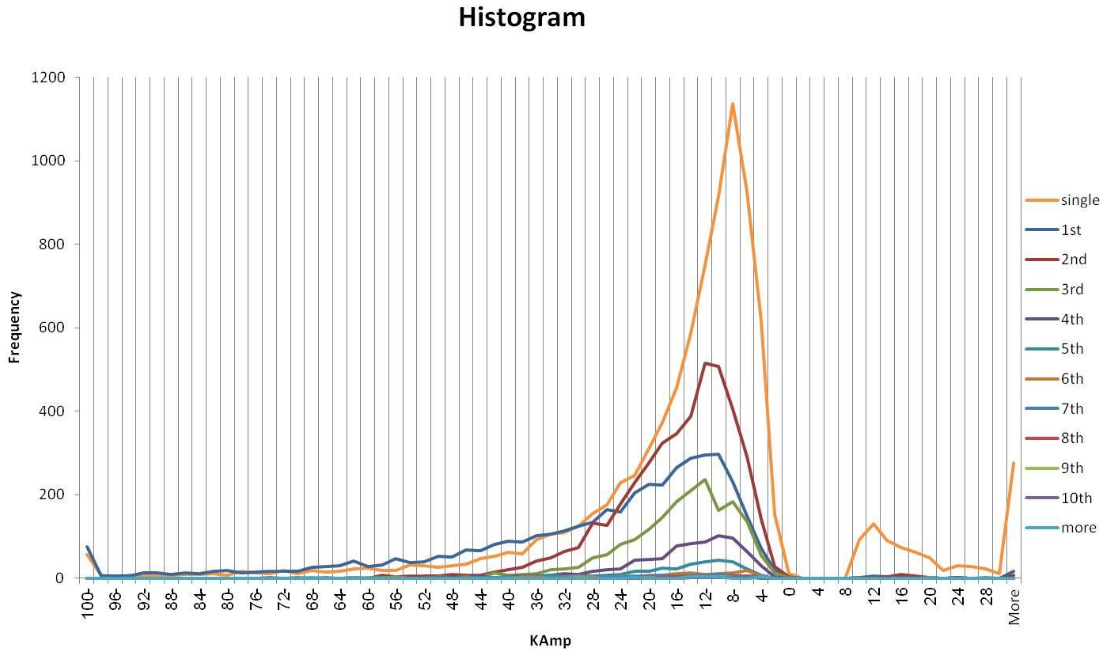

**Fig. 7.** The distribution of peak current [kA] for single- and multiple-stroke flashes in the 30 October storm.