Lightning flash multiplicity in eastern Mediterranean thunderstorms

Yoav Yair[1], Sigalit Shalev[2], Zippy Erlich[3], Alexander Agrachov[4], Eugene Katz[5], Hadas Saaroni[2], Colin Price[4] and Baruch Ziv[1]

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

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Corresponding author: Prof. Yoav Yair
Dept. of Natural Sciences, The Open University of Israel
1 University Road, POB 808, Ra'anana, Israel 43537
E-mail: yoavya@openu.ac.il / yoavyair@gmail.com
Phone: +972-9-7781217 Fax: +972-9-7780661

Abstract

Cloud-to-ground lightning flashes usually consist of one or several strokes coming in very short temporal succession and close spatial proximity. A commonly use method for converting stroke data into flashes is using the National Lightning Detection Network (NLDN) 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 (1.8.2009-31.7.2010). We computed the multiplicity, the percentage of single stroke flashes and the geographical distribution of average multiplicity values for thunderstorms in the Eastern Mediterranean region. Results show that for the NLDN 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 2009/2010, showing that large deviations from the mean values can occur in specific events.

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נמחק: single vs. multiple-stroke

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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. There are several lightning detection networks operating in the US, with varying stroke-to-flash conversion standards. In the NLDN, before its 1994–95 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 2.5º 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

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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 values determined by the NLDN according to the two different methods (the pre- and post-upgrade algorithms) 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 NLDN and found that in most regions the mean negative multiplicity was lower than 2.6. In general, multiplicity increases with higher negative peak currents (first stroke peak current). Analyzing 10 years 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 1989–94, subsequently decreasing to slightly over 2.0 during the period 1995–98. 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 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 to 2.6. The multiplicity values are affected by improved detection ability as a result of some upgrades to the NLDN, 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 2002–03 upgrade. The mean multiplicity for the Austrian Lightning Detection and Information System (ALDIS) was 2.21 and for the FM-System

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נמחק: Two important insights emerge: (a)

נמחק: 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

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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). Matsui and Hara (2011) analyzed lightning data in Japan and conducted a comparison of the NLDN criteria with those used by the JLDN. The mean negative multiplicity was found to be 2.13 and the positive multiplicity was 1.18. They found that the NLDN criteria tend to slightly overestimate the multiplicity values (2.23 and 1.19 respectively), because the NLDN assigns strokes into flashes in larger area compared to the JLDN. The distribution of multiplicity values for the two algorithms is only marginally different (Fig 3 and 4, there).

In Israel, the percentage of negative single-stroke flashes reported by ILLS for the period 2000 to 2007 was 38.5% (Katz and Kalman, 2009). These results were based on the updated NLDN algorithm, which used thresholds of 0.5 sec and 10 km. The mean value of the stroke to flash ratio was found to be 2.7 (this value was obtained by using a different averaging method which excludes flashes with only one stroke). In order to convert this value to the standard multiplicity, we use m = (1-0.385)*2.7+0.385*1=2.05, which properly reflects the stroke-to-flash ratio for the entire data-set.

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If multiple strokes of a single cloud-to-ground (CG) flash indeed hit the same physical location in terms of geographical coordinates, it would be logical for the algorithm for grouping strokes into a flash to 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

נמחק: 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,

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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 United States in 1996) was 500 m (Cummins et al. 1998a). If multiple strokes indeed hit the same location, and if the 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. According to that work, 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. 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 94ms for +CG, which is about 1.5 times greater than the average inter-stroke interval in negative CG flashes (60ms). 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_{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_{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

Lightning in the Eastern Mediterranean and Israel occurs primarily in winter, and concentrated in the months November-January. Summer months are completely devoid of thunderstorms and any electrical activity. In winter, lightning is most often found in cold-fronts of Cyprus lows which are formed over the warm sea and move eastward toward Israel (Ziv et al., 2009). The clouds that generate lightning in these synoptic conditions are compact cumulonimbus clouds with vertical dimensions of 5-7 km often embedded within a larger matrix of shallower convective precipitation regions. They exhibit intermittent electrical activity with low flash rates and resemble lightning activity over the Sea of Japan (Kitagawa and Michimoto, 1994), which is remarkably different from summer thunderstorms in the US and Europe and the tropical activity in Brazil. Only in few rare storms (1-2 per year), that occur when Red-Sea trough conditions exist (in fall months October-November) does lightning activity resemble that which is found in the tropics.

In the present study we used stroke data for the period 1.8.2009-31.7.2010 (later referred as year 2009/2010) 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 was estimated to be > 80% (Y. Katz, personal communication), and it decreases with distance from the network center (Figure 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).

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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, we try to assess if a value of 0.2 s may better represent the multiplicity compared with the nominal 0.5 s. Similarly, as 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, a spatial range of 10 km may 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.

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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).

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

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 NLDN criteria

Figure 1 shows the multiplicity distribution of N_t=10,754 negative CG strokes above Israel when using the NLDN parameters for grouping strokes into flashes (10 km, 0.5 sec). 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)

מעוצב:מדורג ממוספר + רמה: 2 + סגנון מספור: 1, 2, 3, … + התחל מ: 1 + יישור: לשמאל + מיושר ב: 4.1 ס"מ + כניסה ב: 40.2 ס"מ

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מעוצב:גופן: נטוי, גופן עבור עברית ושפות אחרות: נטוי, כתב תחתי

נמחק: flashes

מעוצב:גופן: נטוי, גופן עבור עברית ושפות אחרות: נטוי

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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 for 103 strokes. The percentage of single-stroke flashes reported by the NLDN 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 NLDN for these same regions.

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The distributions in Figures 2a and 2b reflect the inter-stroke characteristic found for the study period. Here N_s 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 93ms. 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 61ms 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.

מעוצב:גופן: נטוי, גופן עבור עברית ושפות אחרות: נטוי

מעוצב:גופן: נטוי, גופן עבור עברית ושפות אחרות: נטוי, כתב תחתי

3.2 Mean multiplicity using different grouping criteria

מעוצב:מדורג ממוספר + רמה: 2 + סגנון מספור: 1, 2, 3, … + התחל מ: 1 + יישור: לשמאל + מיושר ב: 4.1 ס"מ + כניסה ב: 40.2 ס"מ

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 (Figure 3). Table 1 is reproduced from Rakov and Huffins (2006) 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 NLDN 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 67% when using different range thresholds, and from 42% to 71% based on both different range and time 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 assumed to be >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 NLDN 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.

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The geographical distributions of the mean negative multiplicities for two different sets of thresholds are shown in Figure 4. We show multiplicity distribution map for the NLDN 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 100 km^2. For the regular ranges (4a), the highest multiplicity of values in the range of 2.4-6 strokes per

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flash are seen above the Mediterranean Sea close to the coastline. In contrast, values exceeding 1.5 are very rare for the stricter thresholds (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, as one would expect the land area to have better and more abundant contact points to the approaching stepped leader (e.g. buildings, trees, power-lines etc.), and hence the likelihood for repeated strokes to the same point should be greater than above the relatively flat sea-surface.

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3.3 Number of ground contact points

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Research shows that the number of contact points changes with the number of strokes, and increasing the stroke order leads to an increasing likelihood of more ground contact points. 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 Figure 2a), high multiplicity strokes have contact points that are distributed with an inter-stroke distance usually less than 2 km.

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Three such events (named E1, E2 and E3) are shown in Figure 5 (a-c). Event E1 from the 18th January 2010 at 13:41 GMT had the highest number of strokes: 16

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Event E2 from the 26th February 2010 at 15:50 GMT includes 15 strokes and event E3 from the 7th December 2009 at 11:55 GMT includes 13 strokes. The numbers in Figure 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, as shown by the respective error ellipses (Figure 5 e-f). The tight clustering of most of the strokes in all three events suggests that the flashes had more than one groun termination point, but it was still within less than 2.5 km from the main strike point.

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3.4 The storm of 30 October 2009

מעוצב:גופן: 12 נק', מודגש, גופן עבור
עברית ושפות אחרות: Miriam, 12 נק',
מודגש

מעוצב:מדורג ממוספר + רמה: 2 +
סגנון מספור: 1, 2, 3, … + התחל מ: 4
+ יישור: לשמאל + מיושר ב: 90.2 ס"מ
+ כניסה ב: 27.2 ס"מ

During October 30th 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 hours starting at 04:00 UT, the ILLS registered a total of 20696 strokes, of which 19728 were negative cloud to ground strokes (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 extending offshore. A similar pattern was reported by Altaratz et al. (2001) indicating that lightning

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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 strokes along the day. When applying the NLDN criteria for grouping the strokes into flashes, the results for negative CGs show a multiplicity of 2.06 when considering all 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 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. These changes reflect the sensitivity of 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 negative multiplicity found for the stroke data over Israel recorded in the year 2009/10 using the NLDN algorithm, including single-stroke flashes is 1.73. This value is lower than what is reported in other studies for summer storms, and lower even when compared with Japan (2.13) that has similar lightning activity

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Discussion

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נמחק: general

characteristics as Israel (Yair et al., 2009). The other multiplicity value for Israe which can be used for comparison is the one computed by the IEC for the years 2000-2007, which was 2.7 (Katz and Kalman, 2009). That value computed is taking i account only flashes with two or more strokes (m≥2), and is corrected to 2.05.

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, lower than the NLDN-based value of 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 mos studied globally (Cummins et al., 1998b, Schulz et al., 2005).

The temporal threshold of maximum 0.5 seconds between any two successive strokes in a flash 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). In this work we considered a safe margin of more than twice the average inter-stroke interval and conclude that using a maximum temporal range of 0.2 s (200 ms) between successive strokes should suffice. Similarly, a maximum spatial range o 10 km may be too large and may misclassify independent (separate) flashes as subsequent strokes of a single flash. Most video-based studies show a separatio

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נמחק: The multiplicity for flashes with m>=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.

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range of less than 2.5 km between two ground termination points of the same flash. We therefore conclude that a spatial range of twice the stated average accuracy of the lightning location system may be sufficient, especially for winter-type storms that exhibit small dimensions and tighter spatial distribution of ground termination points. This may lead to some multi-grounded flashes to be misclassified as separate flashes. 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.

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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 clear 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).

Acknowledgments

This study was supported by the Israeli Science Foundation (ISF, grant No. 108/10) and by the Open University Research Authority. The authors thank the Israeli Electrical Company (IEC) for providing the lightning data.

List of Figures

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Figure 1 - The multiplicity distribution in thunderstorms in the study area**.**

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

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מעוצב:גופן: לא מודגש, גופן עבור עברית ושפות אחרות: לא מודגש

Figure 3 - Average multiplicity of negative cloud to ground flashes as a function of maximum stroke separation distance for a range of inter-stroke time intervals**.**

Figure 4 - (a) The negative ground flash multiplicity for thresholds of 0.5 s and 1C km. (b) The negative ground flash multiplicity for thresholds of 0.2 s and 2.5 km.

Figure 5 – Spatial distribution of succeessive strokes in 3 different lightning event with high multiplicity values, with the respective error ellipses. (a) Event E3, 7.12.2009 11:55 GMT, m=13 (b) Event E2, 26.2.2010, 15:50 GMT m=15 (c) Event E1, 18.1.2010 13:41 GMT, m=16. (d, e, f) the respective error ellipses for the three events.

Figure 6 - (a) The distribution of strokes for the storm of 30.10.2009. (b) The tempora distribution of strokes along the day.

Figure 7 – The distribution of peak current [kA] for single- and multiple-stroke flashes in the October 30th storm. "Single" refers to flashes with one stroke, and the different lines refer to the distribution of peak current as a function of stroke order ir events when m≥2.

Figures

Figure 1

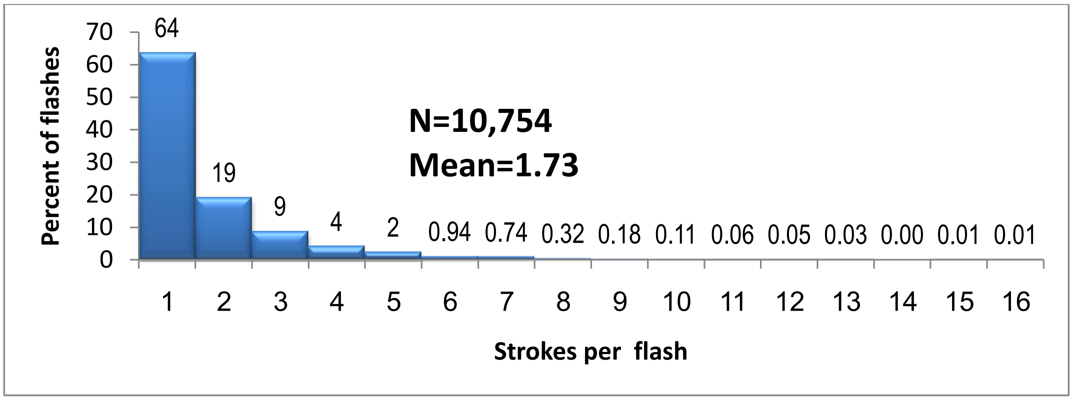


Figure 2a

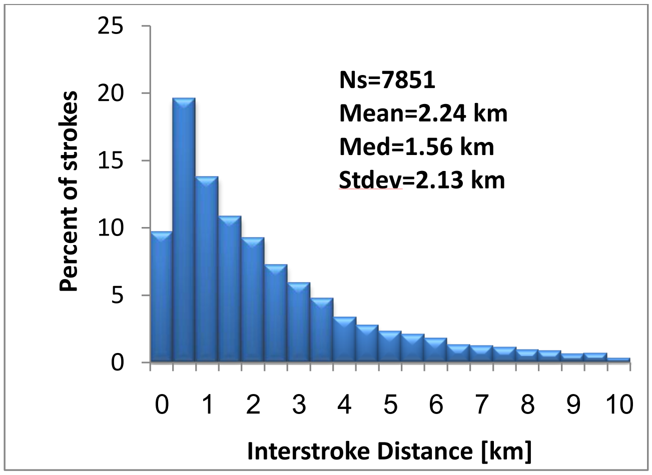


Figure 2b

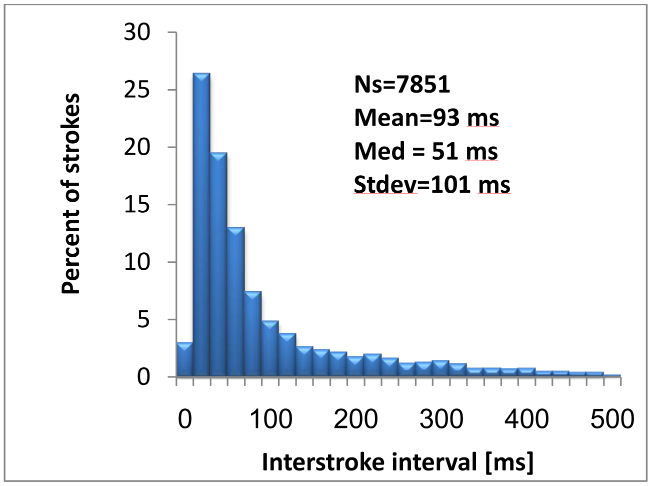


Figure 3

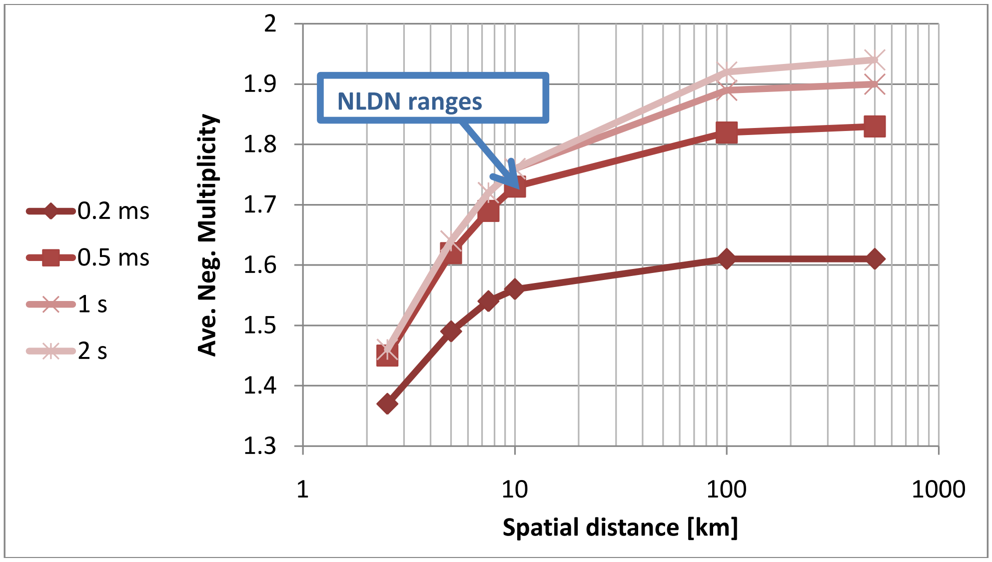


Figure 4

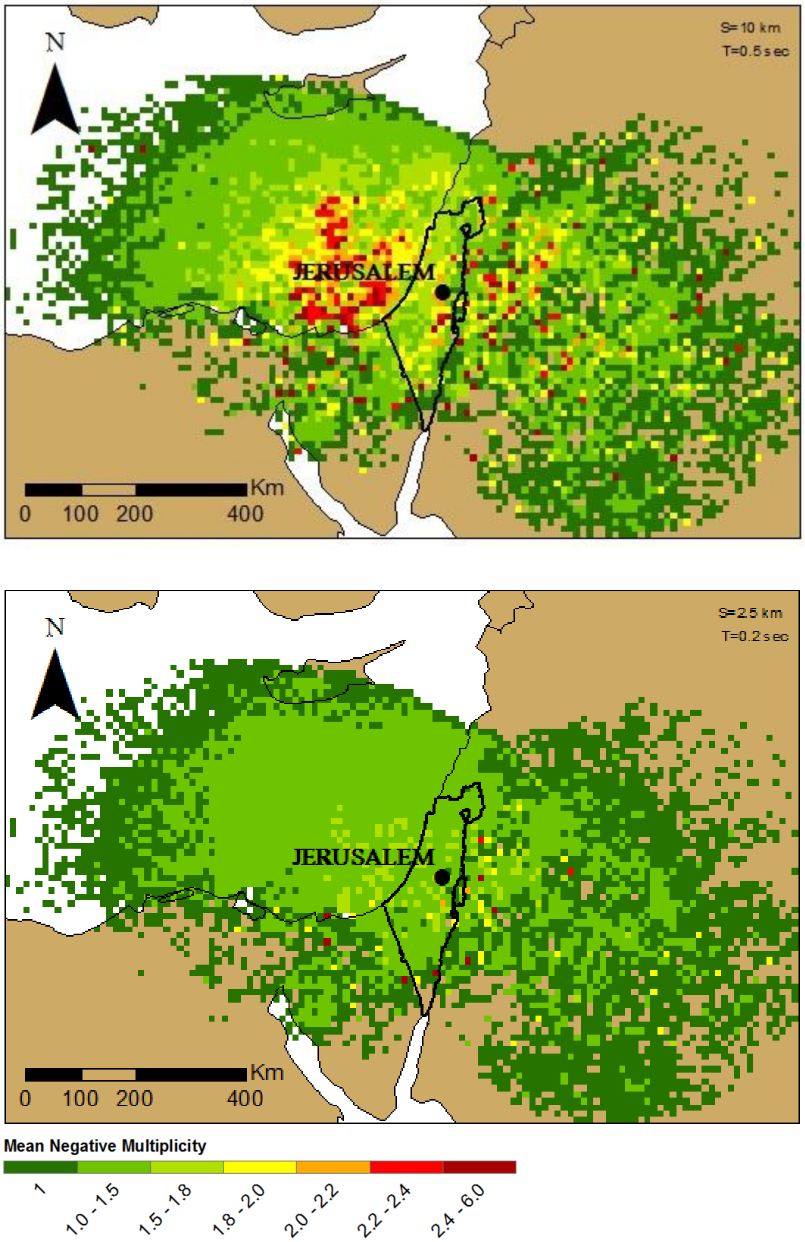
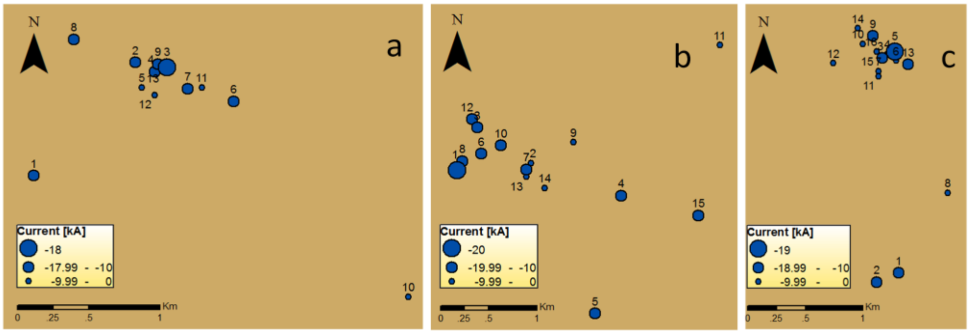
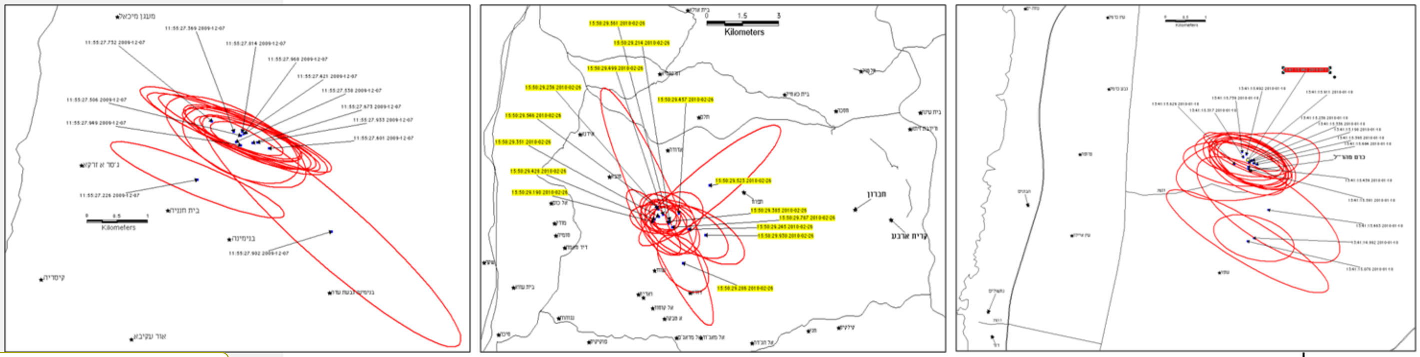

N
S=10 km
T=0.5 sec
JERUSALEM
Km
0 100 200 400
N
S=2.5 km
T=0.2 sec
JERUSALEM
Km
0 100 200 400
Mean Negative Multiplicity
1
1.0 - 1.5
1.5 - 1.8
1.8 - 2.0
2.0 - 2.2
2.2 - 2.4
2.4 - 6.0

Figure 5





מעוצב:גופן: 12 נק', מודגש, גופן עבור עברית ושפות אחרות: 12 נק', מודגש

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Figure 6a

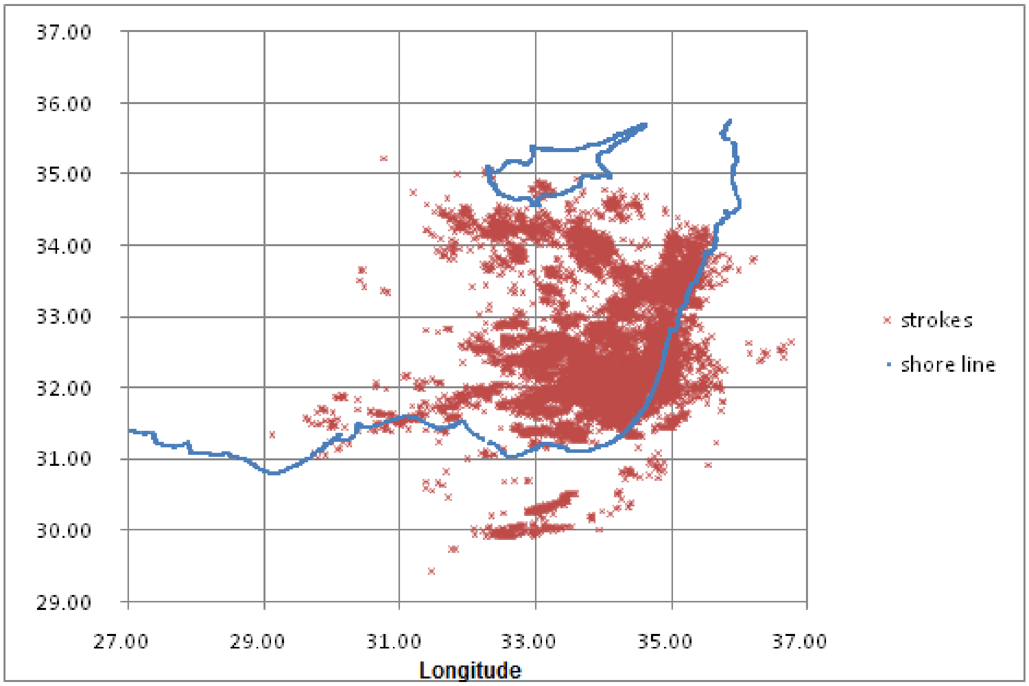

37.00
36.00
35.00
34.00
33.00
32.00
31.00
30.00
29.00
27.00
29.00
31.00
33.00
35.00
37.00
Longitude
strokes
shore line

Figure 6b

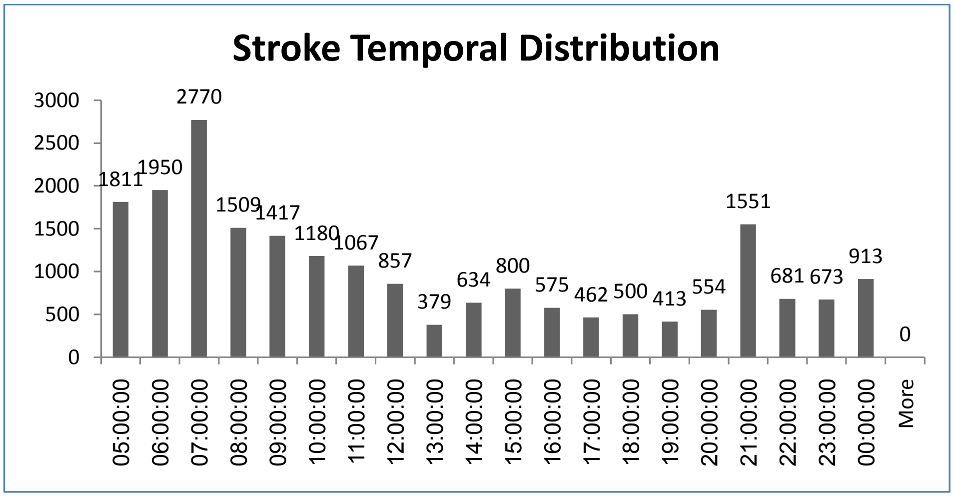
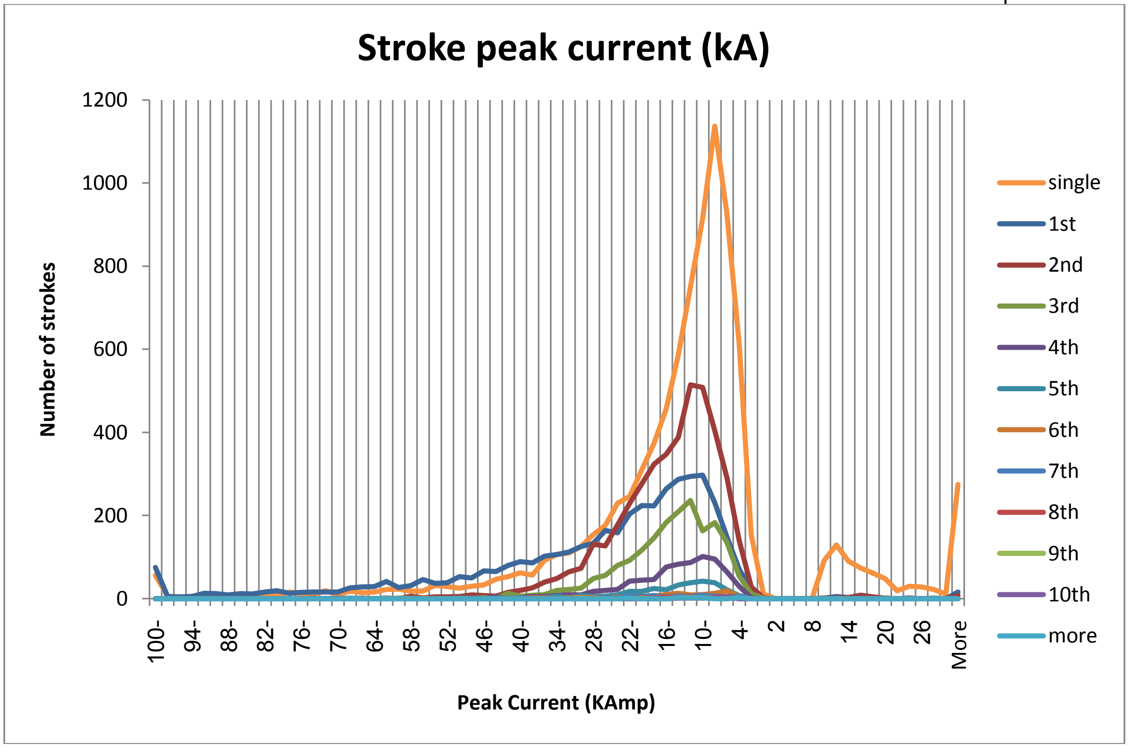

Stroke Temporal Distribution
3000
2500
2000
1500
1000
500
0
1811
1950
2770
1509
1417
1180
1067
857
379
634
800
575
462
500
413
554
1551
681
673
913
0
05:00:00
06:00:00
07:00:00
08:00:00
09:00:00
10:00:00
11:00:00
12:00:00
13:00:00
14:00:00
15:00:00
16:00:00
17:00:00
18:00:00
19:00:00
20:00:00
21:00:00
22:00:00
23:00:00
00:00:00
More

Figure 7


Stroke peak current (kA)
Number of strokes
1200
1000
800
600
400
200
0
100-
94-
88-
82-
76-
70-
64-
58-
52-
46-
40-
34-
28-
22-
16-
10-
4-
2
8
14
20
26
More
Peak Current (KAmp)
single
1st
2nd
3rd
4th
5th
6th
7th
8th
9th
10th
more

Tables

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 (0.5s, 10km)**	**2009-2010**	**231,347**	**1.6**	**17**	**42**
	(0.5 s, 5 km)			1.4	17	52
	(0.5 s, 2.5			1.3	16	67
	(0.2 s, 2.5			1.2	16	71
	Israel (0.5 s, 10km)	**2009-2010**	**18,611**	**1.7**	**17**	**37**
	(0.5 s, 5 km)			1.6	16	42
	(0.5 s, 2.5			1.5	16	52
	(0.2 s, 2.5			**1.4**	**16**	**58**

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