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LETTER

Allowed and forbidden zones in a Lightning-strokes spatio-temporal differential space

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Abstract

In this work, we analyze time series of lightning strokes as detected by an LF/VLF network, over the Eastern Mediterranean during winter storms. The strokes’ raw data is examined without pre-grouping it into flashes. A distance-versus-time differential space (termed dRvsdT) is introduced, examining the intervals between successive strokes. While it loses information on the strokes’ exact time and location, it clusters common properties of the time and space intervals. The clusters on the dRvsdT space point on strokes within a flash (< 1 s), strokes that occur almost simultaneously but in remote thunderclouds (located 10 s–100 s km away), the recharge time of a thundercloud (10 s of sec, a time-lag when strokes cannot occur), and counts of local and remote flashes. This method and its implications for flash determination and properties are universal and can be used for similar measurements around the globe.

1 Introduction

Lightning flashes are a key process in the global electrical circuit (e.g., Wilson 1929, Williams 2005). Nonetheless, fundamental questions in this field are still open due to measurement limitations and the wide range of temporal and spatial scales involved in this phenomenon.

Lightning is formed by cumulonimbus clouds that contain strong updrafts, super-cooled droplets, mixed-phase hydrometeors, and ice particles; all are necessary ingredients for the non-inductive mechanism, which is considered to be the main charging mechanism in clouds (Saunders 2008). The charge is separated on the cloud-scale into a few layers and the most simplistic model describes it as a tripole (Williams 1989). Most lightning flashes are intra-cloud (IC) flashes, meaning they neutralize charge centers within a cloud or in adjacent clouds. The ratio of IC to Cloud-to-Ground (CG) flashes depends on the latitude and is estimated to be ~2 over the Mediterranean region (Mackerras and Darveniza 1994). Most CG flashes are negative (transfer negative charge to the Earth’s surface). Negatively charged flashes constitute 87%–94% of the CG flashes over the Eastern Mediterranean during wintertime (Altaratz et al. 2003, Ben Ami et al. 2015). Negative flashes last up to ~1 s and may consist of several return strokes, separated by a few tens of milliseconds (Rakov and Uman 2003; chapter 4). The first return stroke follows the channel of the stepped leader and the next ones either recur along the same channel or through a new channel that may be located up to several kilometers away from the first ground contact point (Rakov and Uman 1990). The first return stroke was shown to have a stronger peak current compared to the subsequent ones (Berger et al. 1975, Chowdhuri et al. 2005, Saba et al. 2006b, Poelman et al. 2013). Positive CG flashes usually consist of a single return stroke and have a higher peak current compared to the negative ones (Rakov 2003). The characteristic timescales of the charge separation processes and electric field buildup within a thundercloud (the average time between subsequent flashes) range between seconds to minutes. It depends on the thunderstorm characteristics, like the updraft magnitude, the depth of the mixed-phase region, and the fluxes of liquid water, graupel and ice-mass (Deierling and Petersen 2008, Deierling et al. 2008). Nevertheless, even within a specific
storm, it varies as it depends on flash polarity, multiplicity, and peak current (Telesca et al 2005, Zoghzoghy et al 2013). LF/VLF (LF; 30–300 kHz; VLF: 3–30 kHz) based networks, like the one used in this study, measure the variations in the electromagnetic field. Thus, the polarity, peak current, ground striking point, and impact time can be approximated (Rakov and Uman 2003; chapter 17). The physical understanding of charging and discharging processes based on this limited measured information is challenging. Given that those processes depend on many different factors, as written above, even basic knowledge such as how to group the strokes into flashes, involves a high level of uncertainty and depends on chosen thresholds. Previous works examined lightning strokes (and flashes) time series to study and determine the characteristic timescales related to the grouping of strokes into a flash, or to recharge process within a thundercloud. Dennis (1970) studied the timing of consecutive flashes in New Mexico thunderstorms and found a lag of 10 s to 100 s of seconds between successive flashes. Yair et al (2009) studied synchronicity using a series of flashes and showed intervals of 0.2 s to 30 min between successive flashes within a thunderstorm. Telesca et al (2005) showed two scaling periods, the first one represents the lag between flashes within individual thunderstorms (on the order of minutes) and the other one, the time between successive thunderstorms (hours). Zoghzoghy et al (2013) analyzed lightning strokes temporal data and showed that a recharge time of a thundercloud is ∼10 s seconds, according to the time lag between successive lightning flashes within a radius of ∼10 km.

In this work, we present a new method that examines together the temporal and spatial intervals between successive strokes, for studying the characteristic scales of flashes and thunderclouds.

2. Data and methods

2.1. Measuring system and data

The lightning strokes data was measured by the Israel Lightning Location System (ILLS, Katz and Kalman 2009), operated by the Israeli electric corporation. The ILLS was composed of 7 LF/VLF sensors until 2007 when it was upgraded to 8 sensors (see location in figure 1); five are electric-field based, two are magnetic field detectors, and one detects both types of fields. The detection algorithm is based on the time of arrival and magnetic field direction techniques (Cummins et al 1998). The system retrieves information on the peak current, polarity, location, and time of impact of the GF (Shalev et al 2011).

The detection efficiency over the center of Israel (covered by all sensors) is 80%–90% (Yair et al 2014). The spatial detection accuracy and temporal resolution for the detection of successive strokes are 500 m and 15 μsec, respectively (Katz and Kalman 2009, Yair et al 2014). At more than 100 km from the Israeli coast, the detection efficiency is reduced to 50%.

In this study, the Region of interest (ROI) was set over the Eastern Mediterranean Sea (see figure 1) and limited to 150 km from the center of the network. It was selected over the uniform sea surface in order to minimize detection efficiency errors while obtaining sufficient statistics. Days with less than 20 strokes per day over the ROI (indicating weak electrical activity) and positive peak currents smaller than 8 kA (suspected to be IC flashes; Cummins et al 1998) were omitted from the dataset. Overall, the data used in this study include the time and location of 50,318 CG strokes detected during 99 days between December and February of the 2004 to 2010 winters.

Figure 1. Spatial distribution of all detected strokes for December—February (2004–2010). The location of the network detectors is marked by black stars. The study region, over the Mediterranean Sea, is marked by the red curve. The coastlines are marked in blue.
2.2. Method: the dRvsdT differential space
We analyze sequences of lightning strokes as detected by an LF/VLF-based network. All the strokes detected during the study period, over the ROI, were ordered according to their time of impact, creating a list of successive strokes. The analysis examined the time-difference \((dT)\) and distance \((dR)\) between successive strokes (up to \(dT\) of 3 h between strokes). We span the 2D histogram of the \(dT\) and \(dR\) differential data (termed the dRvsdT space). By doing so, we lose the information of specific locations (in the geographical domain) and exact impact times of strokes and gain the ability to cluster common properties of the intervals between them. Due to the wide time and space ranges of \(dT\) and \(dR\), from ms to hours and from meters to 100 s km, the dRvsdT space is presented on a logarithmic scale. In addition, we introduce the pair-analysis, in which we collect sequential strokes (form the dRvsdT space) and compare their average peak-currents to further support the interpretation of the dRvsdT clusters.

This new dRvsdT space allows us to detect key spatio-temporal characteristics of flashes like the recharge time for a thundercloud or the spatial scale of a flash. These properties are common to all events and they are derived here from the basic raw data of strokes without pre-grouping them into flashes using pre-determined thresholds. The natural thresholds that group strokes into flashes arise from the data.

2.3. Synoptic conditions
The dataset in this work was limited to days influenced by Cyprus-Low (CL) synoptic conditions. The CL is a mid-latitude low-level pressure system that produces ~70% of the boreal winter lightning flashes over the region (Shalev et al. 2011). This low generally forms near the bay of Genoa and moves eastward towards the Eastern Mediterranean (Buzzi and Tibaldi 1978, Shay-el and Alpert 1991). The low is accompanied by a high-level trough that carries cold air. While moving over the relatively warm Mediterranean Sea, the air mass destabilizes, and its moisture content increases (Ziv et al. 2009). Thus, thunderclouds develop over the sea and are advected into land by the western synoptic winds.

Daily maps of mean sea level pressure and wind direction at 925 hPa, both at 00:00 and 12:00 UTC (from the Global Data Assimilation System dataset; GDAS, Kanamitsu 1989) provided information on the synoptic conditions. The criteria used to define CL conditions include the location of the low at sea level, north or west of the Israeli coast, northwest to southwest winds at 925 hPa level, and an absence of a low-pressure system south of Israel (similar to Ben Ami et al. 2015).

3. Results and discussion
Figure 2(c) shows the stroke events’ distribution on the dRvsdT space. The dR projection (integrating along dT) is presented in panel (a), and the dT projection (integrating along dR) is depicted in panel (b). Three separate clusters emerge on the dRvsdT space. Cluster A, centered around 0.03 s and 2.5 km, cluster B, centered around 60 s and 7 km, and cluster C, centered around 33 s and 75 km. An important feature emerges, which is the ‘forbidden zones’ in the dRvsdT space; specific ranges of \(dT\) and \(dR\) that are not occupied by strokes and are part of the rich structure of the differential time-distance space. The forbidden empty range of \(dT\) and \(dR\) between clusters A and B presented in figure 2 is an example and will be explained in detail below.

Cluster A, which appears on the range of short \(dT\) (<1 s) and \(dR\) (<~10 km) on the dRvsdT space, can be related to inter-flash processes, meaning the intervals between successive strokes in multiple-stroke flashes. These relatively short time intervals and distances between strokes are comparable to the known values for multiple-stroke flashes over the study region (Yair et al. 2014) and over other locations around the globe (Saba et al. 2006a, Saraiva et al. 2010). We note that cluster A displays a branch towards higher \(dT\) and \(dR\) values, in which \(dT\) is still <1 s, but the spatial intervals extend to longer distances of ~10–15 km. A possible explanation for this feature is the propagation of an in-cloud leader formed at the tip of the lightning channel (after the first return stroke) and moves horizontally in the cloud. It can create another stepped leader that would attach to the ground at a new contact point, a considerable distance away from the previous one (Mazur et al. 1995, Montanya et al. 2014, Zoghzoghy et al. 2014).

Cluster B, centered around 7 km and 60 s on the dRvsdT space, is likely related to intervals between flashes produced by the same thundercloud. Since the \(dR\) is relatively short, and the \(dT\) is significantly longer than those in cluster A, cluster B can be regarded as a ‘local flash counter’, gathering the time-space intervals between the last and the first stroke of sequential flashes in a thundercloud (on a scale of ~10 km). Additional analysis was performed to support this interpretation; we calculated the average peak current of the first and the second stroke in all the pairs in cluster B. Each point in cluster B represents an interval between two strokes (a pair): the first stroke is the last stroke of the previous flash and the second is the first stroke in a flash. The results show that the second strokes’ mean peak current is larger, 30 ± 22 kA, compared to 16 ± 14 kA for the first strokes’ mean peak current (708 pairs of strokes). This finding of a larger peak current for the first stroke in a flash (the second...
stroke in the pairs of cluster B) is in agreement with previous studies (Berger et al 1975, Chowdhuri et al 2005, Saba et al 2006b, Poelman et al 2013) and supports our interpretation of the clusters on the dRvsdT space.

Cluster C is characterized by a wide range of $dR$ ($10$ s to $100$ s km) and $dT$ (a few sec to minutes) on the dRvsdT space; therefore, it can be related to the time difference and distances between the last stroke of a given flash and first stroke of the next flash that took place in a remote thundercloud, a ‘remote flash counter’. It shows characteristic intervals in the cloud system scale. Here, again, examination of the mean peak current of all the pairs of strokes in cluster C shows a larger mean peak current for the second stroke in the pair (32 ± 23 kA, the first stroke in a flash) compared to the first one (18 ± 17 kA), for 2,255 pairs. This also shows a stronger peak current for the first strokes in flashes and further supports our interpretation of the clusters on the dRvsdT space.

The electrical activity over the ROI during Cyprus Low events is produced by a cold front or a cold sector. Therefore, it is expected to find several regions of lighting activity along the frontline at each time point that are 10 s–100 s km apart, as shown by cluster C. The forbidden range of $dT$ and $dR$ between clusters A and B is a time-space area where successive strokes are unlikely to occur. This ‘forbidden’ time interval may refer to the characteristic recharging time within a thundercloud, meaning that within this $dT$ range the thundercloud is not likely to produce successive strokes. It is relevant to a single thundercloud since this zone on the dRvsdT space is bounded by a spatial scale of ∼10 km. This interpretation agrees with previous studies (Hussein and Kazazi, 2013, Zoghzoghy et al 2013) that showed a delay of several to 10 s of seconds between successive flashes within the same thundercloud. This delay is a proxy measure for the time of charge separation and electric field buildup processes within thunderclouds (Yair 2008).

4. Summary

Using raw data measured by the Israel Lightning Location System (ILS) during wintertime Cyprus Low events, we obtained spatio-temporal characteristics of strokes and flashes over the Eastern Mediterranean. Analyzing strokes data on a spatio-temporal interval space (dR versus dT between successive strokes; dRvsdT) without using pre-determined thresholds for grouping strokes into flashes (as usually done with such measurements) enabled us to obtain the characteristic time and spatial scales of flashes.

This new dRvsdT space representation highlights the significance of the time difference between successive strokes, as opposed to the distance between them, in the process of grouping strokes into flashes. The grouping of strokes into flashes is clear using a maximal time-lag of ∼1 s between successive strokes while doing so based on the distance between them does not provide well-defined results (figures 2(a), (b)). Using the two criteria together (distance and time intervals), provides the best separation between the clusters on the dRvsdT space; hence the optimal grouping of strokes into flashes. The clusters mark strokes within a flash (<1 s), a recharge
time of a thundercloud (10 s sec), and count local and remote flashes (located 10 s–100 s km away). The interpretation of the clusters on this space is supported by mean peak currents calculations exhibiting larger currents of the first strokes in flashes.

The proposed method is demonstrated in this work on Eastern Mediterranean winter lightning data but it is applicable for similar data collected by LF/VLF detection networks worldwide. It can be used for accurately grouping strokes into flashes and characterizing their properties, and for following the evolution of the characteristic scales (of flashes) as a function of the environmental conditions.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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