

# Interdependence and Memory in Lightning Flash Sequences

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**ABSTRACT:** The discharges of lightning flashes in different, physically separate, convective cells are traditionally considered to be a memory-less system of stochastic, independent events as the electric field within any individual cell exceeds the local breakdown threshold. The present work offers additional insight into the properties of the network of thunderstorm cells, suggested to be mutually coupled and synchronized by Yair et al. (2006, 2009). We analyzed lightning data from a storm that occurred on 30.10.2009 in the eastern Mediterranean, which produced over 20,000 cloud-to-ground flashes in less than 20 hours, registered by the LPATS operated by the Israeli Electrical Company. Each half-hour of the storm was separately analyzed. Clustering algorithms revealed geographically packed active cells, thus enabling us to assign each flash to a cell. We analyzed pairs of subsequent flashes. We show that the consecutive cells are probabilistically interdependent – when the network is up to creating a flash in a new cell, it remembers the cell of the previous flash. Furthermore, the inter-arrival time between flashes occurring in *same cell* follow a highly skewed, non-exponential distribution, which means that the network remember the elapsed time. Finally, there is an inverse relation between the interdependence level in the network, quantified by its mutual information, and the median of that inter-arrival time distribution of flashes within the same cell; higher levels of interdependence decrease the median down to a certain lower bound. That is, the interactions between the cells in the network accelerate the creation of flashes within cells, up to a critical limit, which represents the minimal charging time in clouds.

## 1. Introduction

A Lightning flash is characterized by its location, associated with a convective cell, and time of occurrence. The simplest assumption regarding the sequence of lightning flashes would be that it is the outcome of a superposition of *independent purely random* (Poisson) processes, each associated with a convective cell. This assumption means that the inter-arrival time between consecutive pair of flashes is exponentially distributed, so a flash does not remember the elapsed time since previous flash, and their locations are independent, so they do not remember their previous cell. In this work we question the validity of these assumptions. It has already been suggested by Yair et al. (2006) that the lightning activity in separate thunderstorm cells may be described by a network of interacting cells that are influencing the times of flash generation, which may eventually reach synchronicity, thus flashing in phase. Yair et al. (2009) analyzed data obtained by lightning location systems for several storms and suggested that thunderstorm cells can be described as leaky integrate-and-fire oscillators (Ernst et al., 1995), which has to reach a critical level before discharging and generating a flash. Mutually "linked" cells may thus shorten the charging time of adjacent cells, leading to clustering of flash sequences and synchronicity. In a recent work, Soula et al. (2010) reported that CG flash sequences in sprite-producing storms exhibit "a kind of synchronicity", although they did not observe spatial clustering of the flashes, but rather a clear trend toward grouping in sequences. They suggested that the first, strong CG in a sequence neutralizes large amounts of charge which facilitate the discharging of other parts of the thunderstorm cell. Looking at the open cellular structure in cloud fields, Feingold et al. (2010) show that mutual interaction between precipitation-driven outflows in clouds lead to the emergence of an oscillating, self-organized system with a characteristic cell

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size and precipitation frequency. Since precipitation processes and charging are inter-related, such findings support the ideas of mutual interaction between adjacent clouds.

## 2. Analysis and Results

We used CG lightning data obtained by the Israel Electrical Company LPATS from a storm over Israel and the Mediterranean Sea that occurred on Oct. 30, 2009, from 4:00 to 24:00, with over 25,240 strokes. In order to avoid the issue of multiplicity, multiple strokes were grouped to flashes, using the criteria of inter-distance 10 km and inter-arrival time 0.5 sec. This left 19,946 flashes for the analysis. We divided the series of events into a set of 40 half hour storms, each of which was separately analyzed. A clustering algorithm revealed geographically packed active cells. Each flash is thus assigned to a specific cell, which in the physical sense can be regarded as the cumulonimbus cloud that generated it.

### 2.1. Inter-dependence of cells of consecutive flashes

We describe the sequence of cells of flash events by a series of random variables  $\{X_n\}$ .  $X_n = j$  means that the  $n$ 'th flash occurred at cell  $j$ . We performed the *Chi Square Test for independence* of  $X_n, X_{n+1}$ , the cells of consecutive flash events. The test calculates the discrepancy between the joint probability  $\Pr(X_n = i, X_{n+1} = j) \equiv P(i, j)$  for the occurrence of two consecutive flashes at cells  $i, j$ , and the product of  $\Pr(X_n = i) \equiv P(i)$  and  $\Pr(X_{n+1} = j) \equiv P(j)$ , the total probabilities for flashes in cell  $i$  and cell  $j$ , respectively. Note that throughout this paper we assume homogeneity, that is, that the probabilities do not depend on  $n$ . The observed discrepancy is called  $\chi^2$  (chi squared) calculated from the frequencies of lightning events in the data, is an estimate of the dependence between the cells of the consecutive pair of cells. It is significant if it is larger than the  $\chi^2$  critical value. The results for all of the 40 half-hour storms are presented in *Figure 1*. Clearly, all of the storms the discrepancy  $\chi^2$  is significantly larger than the critical value so that the corresponding  $p$  values (not shown) are smaller than 0.05. Thus, at 95% confidence level the assumption that  $X_n, X_{n+1}$  are independent is rejected.

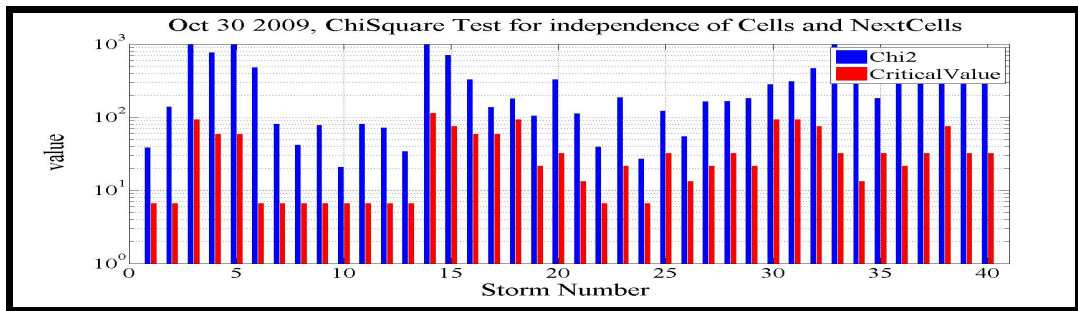


Figure 1: Chi Square test for independence of consecutive cells

The dependence means that the conditional probability  $\Pr[X_{n+1} = j | X_n = i]$ , that is, the probability that a cell of a flash is  $j$ , given that the previous flash was at cell  $i$ , depends on the value  $i$  of that previous cell; An example of this fact for time segment 28 is displayed in Figure 2. In the figure  $\Pr[X_{n+1} = j | X_n = i]$  are grouped, for a given  $j$ . We see that they depend on  $i$ ; flashes have preferences about whereabouts of next flash. Specifically flashes "prefer" that the subsequent flash will be in the same cell. The conclusion is that each of the half hour storms consists of a set of interdependent cells. It is a network of cells.

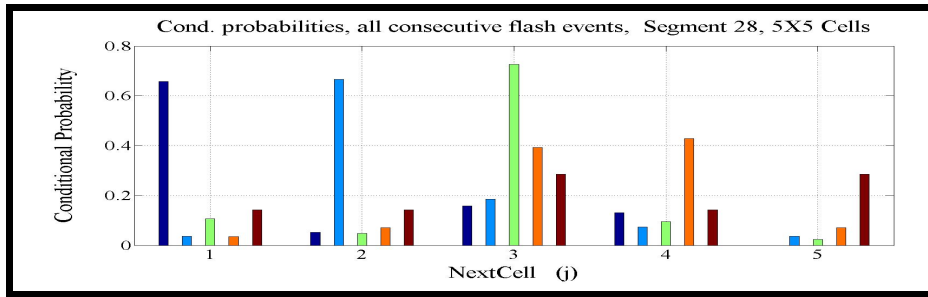


Figure 2: Conditional probabilities for storm 28

## 2.2 Analysis of the inter-arrival times

We analyzed the probability distributions of the *InterFlash\_Time*, the inter-arrival time between two consecutive flashes occurring within the same cell, and of the *InterCell\_Time*, the time interval between the occurrences of first flashes in two (separate) consecutive cells. The empirical characteristics of the distributions are quite different (Figure 3). Specifically, the observed median values of the *InterFlash\_Time* are considerably smaller than the corresponding values of the *InterCell\_Times*; consecutive flashes within a cell are packed in short times. We fitted the 1-parameter exponential function to the *InterFlash\_Time* distribution, calculated the  $\chi^2$  and the associated critical values of the fits (Figure 4). We see that all the  $\chi^2$  values are larger than the critical values, which means that the exponential function does not fit the *InterFlash\_Time* distribution. This suggests that when the network is active within a given cell, it "remembers" the elapsed time since the previous flash.

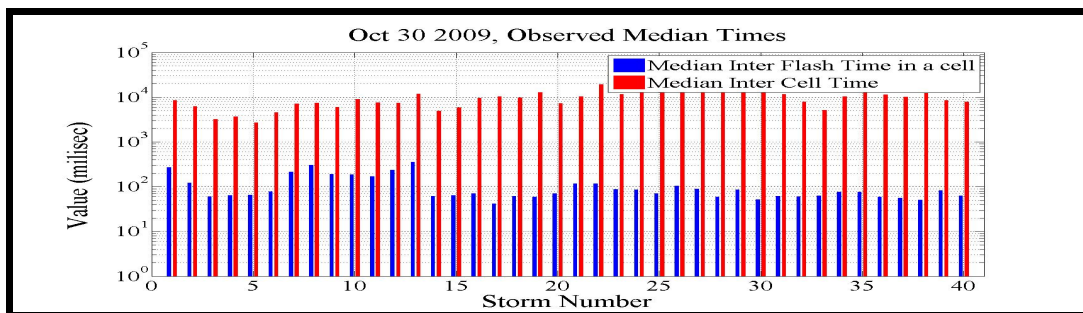


Figure 3: The observed median of Inter Flash and Inter Cell times.

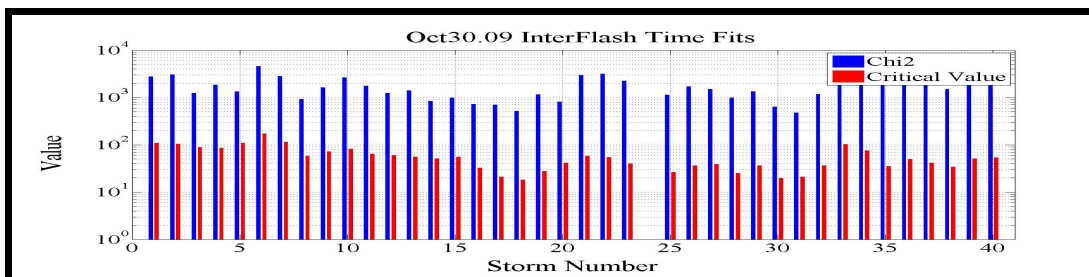


Figure 4: Test of Exponential functions fits to the *InterFlash\_Time* distribution

## 3. The impact of interdependence

The interdependency level in each of the observed half hour storms can be quantified by its *mutual information*; this measures the amount of knowledge about the cell of the  $n+1$ 'th flash ( $X_{n+1}$ ) that is provided by the

knowledge of the  $n$ 'th flash ( $X_{n+1}$ ). If cells of consecutive flashes are independent, the mutual information is zero; otherwise it is a positive number (in bits). The mutual information is given by

$$I(X_n, X_{n+1}) = \sum_{ij} P(i,j) * \log_2[P(i,j)/(P(i)P(j))] \quad (1)$$

In Figure 5 each point represent one half-hour storm: its (x,y) coordinates are the mutual information and the median of the *InterFlash\_Time* distribution of that storm, respectively. We see that storms with weak interdependency (smaller mutual information) have a range of values of the median which are in general higher than the values in storms with strong interdependency. Once the mutual information increases above 0.2 bits, the medians drop down to a “universal” value of about 60 msec; the influence of the cells on each other increases the production rate of flashes in a cell, up to some limit. This limit may represent the minimal charging time it takes the thunderstorm before it can produce a new flash, and is of the order of 60 msec.

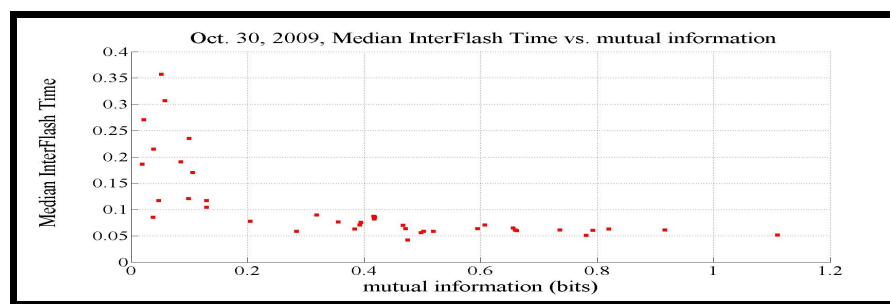


Figure5: The dependence of *InterFlash\_Time* on the mutual information

#### 4. Conclusion

The lightning activity in a multi-cell storm system deviates from a random pattern. It appears that the sequence of flashes has a preference for occurrence that reflects a mutual electrical interaction between clouds. The analysis of inter-arrival times of CG flashes shows that there exists a limit between successive flashes, further supporting the idea of clouds being "integrate-and-fire" oscillators. Ernst et al. (1995) distinguished between inhibitory and excitatory types of coupling in large ensembles of globally coupled oscillators, the latter leading to a prevailing of a mechanism of emerging and decaying synchronized clusters. We therefore suggest that thunderstorms share an excitatory type of interaction, inducing and supporting discharges in separate cells that can lead to transient synchronization of lightning activity.

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