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Multifractal analysis of lightning channel for different categories of lightning

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ABSTRACT

A study from the point of view of complex systems is done for lightning occurred at Diamantina, Sete Lagoas and São José dos Campos, during the summer from September 2009 to April 2010. For the first time, multifractal analyses were performed for different lightning categories: two-dimensional, three-dimensional, non-branched, branched, cloud, cloud-to-ground, single and multiple. We found that when using two-dimensional images of natural lightning embedded in three dimensions to perform multifractal analysis, the interpretation of the multifractal spectrum must be restricted to identification of the multi (mono) fractal character of lightning channel and to estimation of fractal dimension. We have also observed that, on the average, each category has a specific value of fractal dimension. Categories in which branches and tortuosity are more usual, like branched and cloud categories, exhibited largest fractal dimensions due to more complexity of lightning channels. The results suggest that single and multiple lightning have similar complexities in their channels, leading to the same average values of fractal, information and correlation dimensions for both categories.

1. Introduction

Measurements of Lightning electromagnetic radiation have been extensively carried out and have revealed many features of lightning in time domain. For example, from lightning electric field waveform measurements, the average time between K-changes was observed in the range of 8–20 ms (Kitagawa and Brook, 1960; Miranda et al., 2003; Thottappillil et al., 1990). Measurements have also been made in frequency domain using narrow band filters (Horner and Bradley, 1964; Le Vine, 1987; Schafer and Goodall, 1939). Similarly, frequency spectra were obtained by measuring the signal in a wide band measurement system in time domain and Fourier transforming it. This procedure in studies of lightning radiation has widely been used after Serhan et al. (1980). Lightning electric field waveform measurements has also been associated with wavelet analyses to obtain temporal information about lightning spectrum (Esa et al., 2014; Li et al., 2013; Miranda, 2008; Sharma et al., 2011). Measurements of lightning radiation can also be used to verify bifurcation of lightning channel in space (Willett et al., 1995). However, although the powerful procedure of measuring electromagnetic radiation of lightning in time domain can reveal some information of lightning channel behavior in space, the use of images (still pictures, streak photography or videos) have revealed to be a more suitable procedure for observation of lightning behavior in space. Historically, the first observations of lightning images were done by Schonland et al. (1935) and Schonland et al. (1938), and from them other studies have been done (Antunes et al., 2015; Flache et al., 2008; Idone and Orville, 1988; Idone, 1995; Saba et al., 2004; Valine and Krider, 2002; Willett et al., 1995; Winn et al., 1973). Although these studies so far mentioned, are observations of lightning channel geometry (tortuosity or bifurcations), they do not address the fractal or multifractal nature of lightning channel.

It is known that, besides the intensification of the content of high frequency in the electromagnetic spectrum and more jagged radiation fields (Le Vine and Meneghini, 1978), the increase of tortuosity of lightning channel also makes lightning behave as fractal antenna (Valdivia et al., 1997, 1998; Vecchi et al., 1994). Models of fractal dynamics and radiation of intracloud micro-discharges and of sprites have been done by Iudin et al. (2003), Hayakawa et al. (2007) and Hayakawa et al. (2008). Some researchers have seen that radiation fields emitted by lightning are characterized by the same fractal dimension of lightning channel (Gou et al., 2009; Vecchi et al., 1994). However, Lupò et al. (2000) obtained results in which dissimilarities among fractal dimensions of channel and radiation fields were found. There are a lot of studies in the literature, concerning the understanding the fractal nature of lightning. They can range from simulation of electrical

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discharges in dielectric, computational simulation and modelling of lightning channel, measurements of radiation fields up to fractal analysis of still pictures. The results of fractal dimension from this diversity of techniques can be seen in the literature in a range between 1.1 and 1.9 (Amarasinghe and Sonnadara, 2008; Kawasaki and Matsuura, 2000; Lupò et al., 2000; Tsonis, 1991).

The values of fractal dimensions presented by Amarasinghe and Sonnadara (2008) indicate that simulated electrical discharges and surface discharges show fractal dimensions slightly larger than natural lightning. For example, simulation of branching discharges gas by Niemeyer et al. (1984) naturally lead to structures with fractal dimension equals 1.75 ± 0.02. In turn, Tsonis (1991) analyzed a set of lightning photographs and found an average fractal dimension equal to 1.34 ± 0.05.

Most studies on the fractal nature of lightning channels are made from two-dimensional simulation or two-dimensional images. However, computer simulations show that the fractal dimension of a three-dimensional lightning is about 10–13% higher than the fractal dimension of its projection on a plane (Amarasinghe and Sonnadara, 2008; Sañudo et al., 1995). More recently Perera and Sonnadara (2013) made two-dimensional and three-dimensional simulations of electrical discharges. In these simulations they used an improved *Dielectric Breakdown model* (DB model) in which the exponent (η) parameterizes the relationship between the local electric field and the probability of growth of the discharge pattern. They observed "bush" type discharges and "branched" type discharges, depending on the power (η) of the local electric field. According to them, discharge patterns similar to actual lightning were obtained when the exponent η was equal to about 5.2.

According to Lupò et al. (2000), the works developed previously to their work considered only the influence of tortuosity of lightning channels in the results. Thus, they are the first to consider the influence of the branches in the results.

Other works have plunged deeper into the complex nature of lightning. Gou et al. (2007, 2009) found that the return stroke electric signals exhibit strong degree of multifractality and singularity, the multifractal spectrum fits to the modified version of binomial multifractal model and that multifractal spectrum can be regarded as "*fingerprints*" of return strokes. Also, according to Gou et al. (2009), the fractal dimensions of the electric signals of radiation ranged from 1.2 to 1.5 with an average of 1.3 and the peak current of a return stroke has been related to the electric charge deposited in the leader channel by the fractal dimension obtained.

To the best of our knowledge, no study of multifractality of lightning has been done for different categories of lightning. So, as a general objective in this work, we intend to analyze multifractal nature of different categories of lightning. These categories are groups formed by lightning selected according to some specific behavior in space.

For this study, lightning images made by a normal camera were used and eight categories were analyzed.

More specifically, the objectives of this study are:

a) Perform and compare multifractal analysis of two-dimensional natural lightning and three-dimensional simulated lightning;
b) Perform and compare multifractal analysis of non-branched ground lightning (Fig. 1a) and branched ground lightning (Fig. 1b) categories. For both categories of lightning, the term "ground" refers to a cloud-to-ground or ground-to-cloud

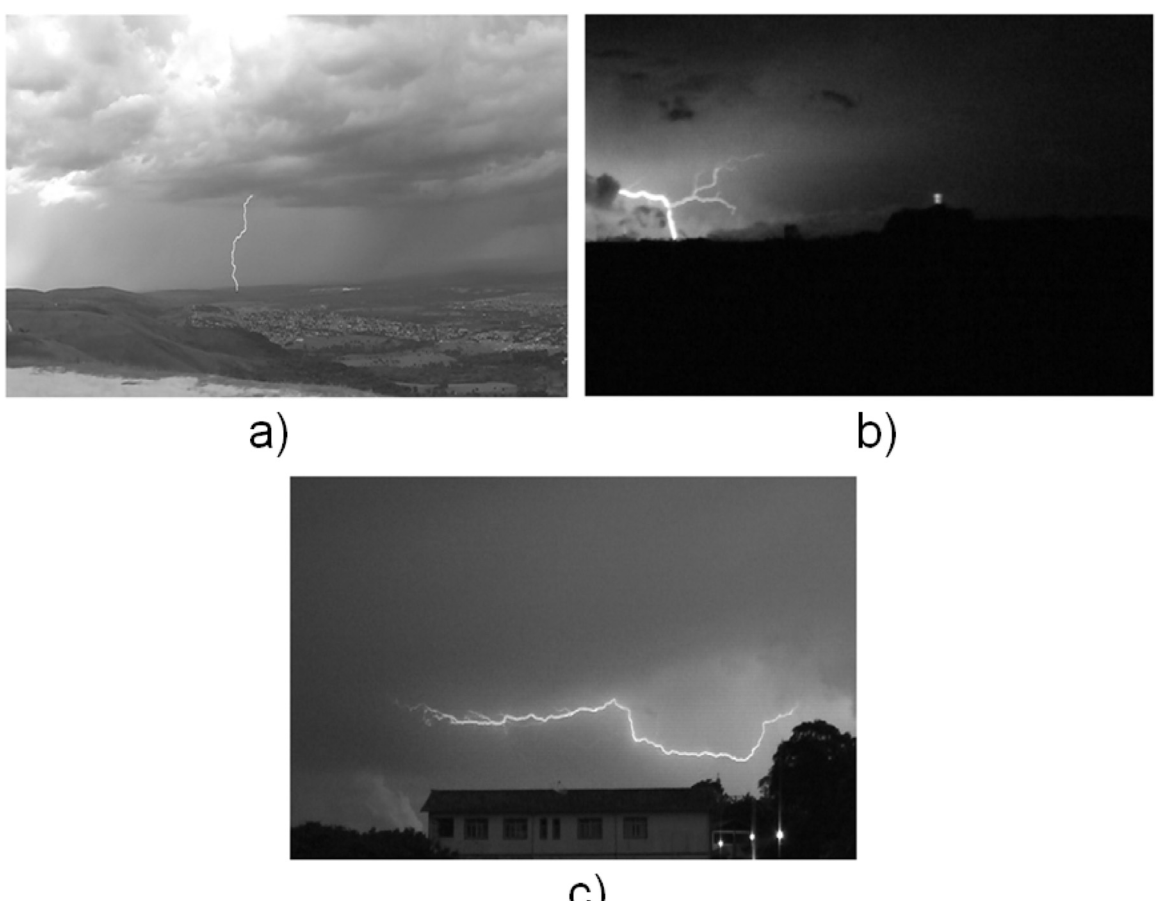

Fig. 1. Exemplification of lightning used in the composition of the categories studied in this work: a) Non-branched ground lightning; b) Branched ground lightning; c) Cloud lightning.