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The role of propagating stress waves on a geophysical scale: Evidence in terms of nonextensivity

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A B S T R A C T

Laboratory experiments have shown that, during a fracture, the breaking of a bond launches a propagating stress wave which may trigger the breaking of other bonds. We examine here the possibility that the same holds on a geophysical scale. Based on a nonextensive approach, we examine whether the transient stresses of seismic waves from a major earthquake (EQ) can trigger a considerably distant significant EQ. We use three different analytical approaches: (i) a recently introduced fragment-asperity interaction model for EQ dynamics based on nonextensive Tsallis statistics; (ii) the Hurst exponent; (iii) organization in terms of Fisher information. We find that the triggered seismicity displays higher nonextensivity, increased persistent behavior, and a higher level of organization. Using the same approaches, we further elucidate the link between the associated precursory kHz electromagnetic (EM) activity and the last stage of the impending EQ generation. We examine whether the statistics of regional seismicity could be a macroscopic reflection of physical processes in the EQ source, as would be expected by the fractal nature of fracture and faulting.

1. Introduction

On 17-Aug-1999, a major ($M_W = 7.4$) earthquake (EQ) occurred at Izmit, Turkey. Brodsky et al. [1] have reported that the Turkish event was followed immediately by small earthquakes occurring throughout much of continental Greece. The authors suggested a link between the activity in Greece (up to a distance of 2000 km away from Izmit) and the Turkish event. We note that laboratory evidence is in agreement with this suggestion. Specifically, Krysac and Maynard [2] have shown that, during the fracture of a brittle material, the breaking of a bond launches a propagating stress wave which may trigger the breaking of other bonds. The time internal between the Turkish and Greek events strongly implies that the large-amplitude dynamic strain of the surface waves was responsible for triggering the regional seismicity. In this regard we note that on 07-Sep-1999 (11:56:50.5 GMT) a catastrophic EQ occurred in Athens (Greece), which is located approximately 650 km south-west of Izmit.

Herein we first investigate, in terms of nonextensivity, whether the transient stresses from the Izmit EQ were responsible for the triggering of the Athens EQ. Specifically, we examine the seismicity of the area of Greece in terms of the nonextensive q-parameter, which characterizes the intensity of long-range interactions between fracture events [3,4]. We estimate the q-parameter based on a recently introduced model for EQ dynamics, according to which two rough profiles interact via

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fragments that fill the gap between them [5,6]. It is found that, before the Izmit EQ, Greek seismicity presents high q-values centered on central and western Greece, while after the Izmit EQ, the higher q-values shift towards central Greece around the Athens area. Moreover, analysis in terms of Fisher information on the one hand and rescaled range analysis (applied on inter-event times) on the other reveal that higher organization and higher persistent behavior were developed mainly around the Athens EQ epicenter after the occurrence of the Izmit EQ.

Preseismic MHz–kHz electromagnetic (EM) activity was also observed a few tens of hours before the Athens EQ. Although these emissions have been well documented as valid anomalies [7–10], their correlation to the characteristics of the corresponding seismicity would further enhance the view that they are of seismogenic origin. Building on the same analytical approaches, we find that the preseismic kHz EM emissions share similar nonextensive features with those obtained from seismicity. (In recent studies we have verified the high persistent behavior and high organization levels of these signals [7,11].) Based on the results of nonextensive analysis, we argue that the activation of a single fault in terms of preseismic kHz EM emissions behaves as a reduced self-affine image of regional seismicity.

This paper is organized as follows. In Section 2, we describe the basic principles of Tsallis nonextensive statistical mechanics and a fragment-asperity model for EQ dynamics based on this approach. In Section 3, we apply a spatial nonextensive analysis of Greek seismicity focusing on the periods before and after the occurrence of the Turkish event. The results are further investigated in terms of complexity (or organization). In Section 4, we focus on the regional seismicity around the Athens EQ epicenter by means of rescaled range analysis. In Section 5, we use the nonextensive model for EQ dynamics to examine the relation between the kHz EM emissions and the foreshock activity of the Athens EQ. In Section 6 we summarize the key findings.

2. Theoretical background

2.1. Principles of Tsallis entropy

The aim of statistical mechanics is to establish a direct link between mechanical laws and classical thermodynamics. Within that context, "extensivity" is one of the crucial properties of the Boltzmann–Gibbs entropy ($S_{\mathrm{B-G}}$) expressing the proportionality with the number of elements of the system. $S_{\mathrm{B-G}}$ satisfies this rule, if the subsystems are statistically (quasi-) independent, or typically if the correlations within the system are essentially local. In such cases, the system is called extensive. However, in the cases where the correlations may be far from negligible at all scales, $S_{\mathrm{B-G}}$ is "nonextensive". Inspired by multi-fractal concepts, Tsallis [3] proposed a generalization of the B–G statistical mechanics, by introducing an entropic expression characterized by an index q which leads to a nonextensive statistics:

$$S_q = k\frac{1}{q-1}\left(1-\sum_{i=1}^{W} p_i^q\right), \tag{1}$$

where p_i are the probabilities associated with the microscopic configurations, W is their total number, q is a real number, and k is Boltzmann's constant. $q \to 1$ corresponds to the standard extensive B–G statistics. Indeed, using $p_i^{(q-1)} = e^{(q-1)\ln(p_i)} \sim 1 + (q-1)\ln(p_i)$ in the limit $q \to 1$, we obtain the standard B–G entropy:

$$S_1 = -k\sum_{i=1}^{W} p_i \ln(p_i). \tag{2}$$

The entropic index q characterizes the degree of nonadditivity reflected in the following pseudo-additivity rule:

$$S_q(A+B) = S_q(A) + S_q(B) + (1-q)S_q(A)S_q(B). \tag{3}$$

The cases $q > 1$ and $q < 1$ correspond to sub-additivity and super-additivity, respectively. The parameter q itself is not a measure of the complexity of a time series. It measures the degree of nonextensivity of the corresponding system. A metric of the dynamic changes of the complexity of a system is the time variations of the Tsallis entropy for a given q (S_q).

2.2. A fragment-asperity model for earthquakes coming from a nonextensive Tsallis formulation

The best-known scaling relation for EQs is the Gutenberg and Richter (G–R) magnitude–frequency relationship [12], given by

$$\log N(>m) = \alpha - bm, \tag{4}$$

where $N(>m)$ is the cumulative number of EQs with a magnitude greater than m occurring in a specified area and time. Parameters b and α are constants.

A nonextensive model for EQ dynamics consisting of two rough profiles interacting via fragments filling the gap has been recently introduced by Sotolongo-Costa and Posadas (SCP) [5]. More recently, this model was revised by Silva et al. [6], in which two crucial ingredients were employed. They use a revised definition for the mean values in the context of Tsallis nonextensive statistics that was achieved in the study of Abe and Bagci [13]. Moreover, Silva et al. proposed a new scaling law, $\varepsilon \propto r^3$, between the released relative energy ε and the size r of fragments. Finally, their approach leads to the following