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Evidence of Nonextensive Statistical Physics behavior of the Hellenic Subduction Zone seismicity

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ABSTRACT

The Hellenic Subduction Zone (HSZ) is the most seismically active region in Europe. Many destructive earthquakes have taken place along the HSZ in the past. In this study we investigate the seismicity of the HSZ based on the science of complex systems. The spatiotemporal distributions of seismicity as well as the magnitude distribution are studied using the concept of Nonextensive Statistical Physics (NESP). Defining five seismic zones and forming an earthquake dataset that covers the period 1976–2009, we apply the NESP ideas to formulate the cumulative distribution functions of the inter-event times and distances and the magnitude distribution along the HSZ. Our results indicate that the nonextensive parameter q_T, which is related with the inter-event time distribution, presents almost similar values in each of the seismic zones and reflects the long term scale of the seismicity evolution in the HSZ. The q_D parameter, which is related with the inter-event distance distribution, presents a significant variation along the seismic zones. This variation is related with the different degree of spatial earthquake clustering in each of the seismic zones of the HSZ. Moreover, in the framework of the fragment–asperity model, the thermostatistical parameter $q_{M,}$ which is related with the frequency–magnitude distribution, could be used as an additional index to inform us about the physical state of each seismic zone along the HSZ. The variations of the q_M parameter are related with the energy release rate in each seismic zone. The models used, fit rather well to the observed distributions, implying the usefulness of NESP in investigating such phenomena exhibiting scale-free nature and long range memory effects.

1. Introduction

The Hellenic Subduction Zone (HSZ) is a highly active seismic belt (Becker and Meier, 2010; Meier et al., 2004) which presents a complex geometry and forms a strongly curved plate boundary (Bohnhoff et al., 2005). This high seismic activity is caused by the subduction of the Adriatic continental lithosphere in the north and the Ionian oceanic lithosphere in the south. The Kephalonia Transform Zone, hereafter will be referred as KTZ, separates the northern part of the Hellenic subduction boundary from the southern one (Royden and Papanikolaou, 2011) (Fig. 1). The southeast trending portions of the Hellenic arc are dominated by compression, while the convergence across the northeast trending portion of the arc is largely left slip (Hollenstein et al., 2008; Royden and Papanikolaou, 2011). The northeast trending portion extends from eastern Crete to southwestern Turkey (Royden and Papanikolaou, 2011). The island of Crete forms the central part of the Hellenic arc (Bohnhoff et al., 2005). The Hellenic arc is characterized by earthquake events of intermediate depths (27–75 km) (Hollenstein et al., 2008). According to Bohnhoff et al. (2005), the distribution of the hypocenters in the south Aegean region follows the Hellenic arc, with the stronger seismic activity to be observed in the eastern part. The Benioff zone reaches ~150 km depth beneath the volcanic arc in the southern Aegean (Papazachos et al., 2000). The evolution of such tectonically active regions is expressed through seismicity and is characterized by complex phenomenology.

In recent years, there is a growing interest concerning an approach to seismicity and other natural hazards based on the science of complex systems and the fractal nature of those phenomena (Bak and Tang, 1989; Bak et al., 1988; Vallianatos, 2009; Vallianatos and Telesca, 2012; Vallianatos et al., 2012a, 2012b). Nonextensive Statistical Physics (NESP) (Tsallis, 1988, 2009), which is a generalization of Boltzmann–Gibbs statistical physics, seems a suitable framework for studying complex systems exhibiting phenomena such as fractality, long-range interactions, and memory effects (Vallianatos and Telesca, 2012; Vallianatos et al., 2012b).

In the present study we use the concept of NESP to analyze the seismicity of the HSZ. We analyze the temporal and spatial properties of seismicity, as well as the magnitude distribution. Moreover, our aim is to find any possible connection between the calculated thermostatistical parameters and their spatial variation along the HSZ. We

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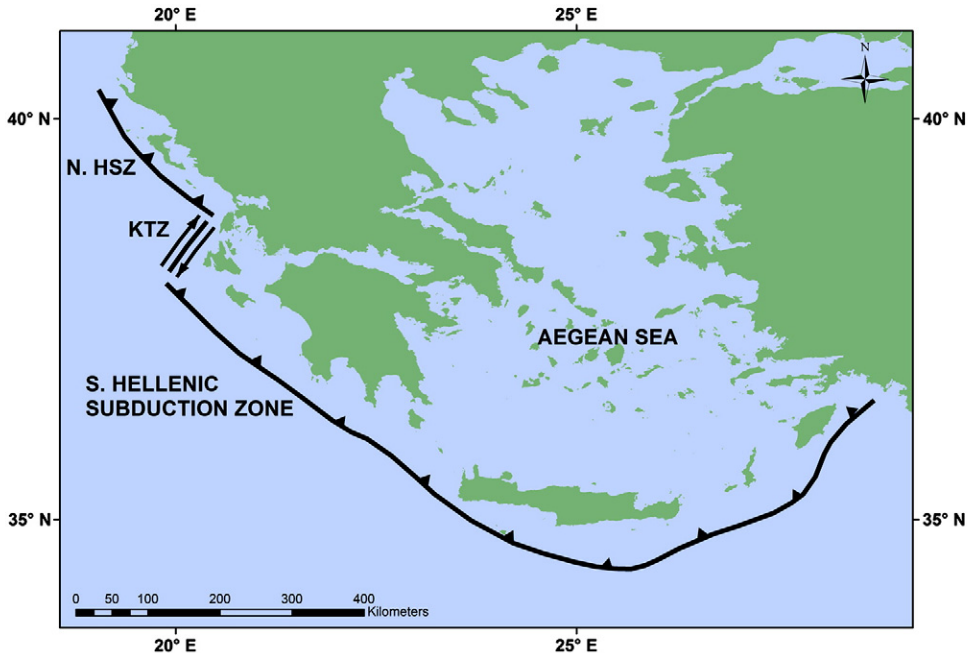

Fig. 1. The active trenches (thick dark lines with solid barbs) for the HSZ, as Royden and Papanikolaou (2011) indicate them. The KTZ separates the northern part (N.HSZ) of the Hellenic subduction boundary from the southern one (S. HSZ).

use the external seismic sources provided in Papaioannou and Papazachos (2000), to define a dataset regarding the subduction zone. Following them, we define five seismic zones and we form an earthquake dataset that covers the period 1976–2009, based on the updated and extended earthquake catalog for Greece and the adjacent areas by Makropoulos et al. (2012).

We note that the applicability of NESP in earth sciences is a new challenging topic as this has been demonstrated in a series of recent publications on seismicity (Abe and Suzuki, 2003, 2005; Silva et al., 2006; Telesca, 2010a, 2010b, 2012; Vilar et al., 2007), natural hazards (Vallianatos, 2009, 2013), plate tectonics (Vallianatos and Sammonds, 2010), geomagnetic reversals (Vallianatos, 2011), and rock physics (Vallianatos and Triantis, 2012; Vallianatos et al., 2011; Vallianatos et al., 2012a).

2. Seismic zones and earthquake dataset

Papaioannou and Papazachos (2000) separated the region of the Aegean and the surrounding area in 67 seismic sources. This separation is based on previous work on seismic zonation, work on seismicity and active tectonics, as well as on geological and geomorphological information. In the present work, we use the external seismic sources, which are associated with the compressional stress field to define a dataset regarding the subduction zone. These sources have axes parallel to the external coast of the area and to the strikes of the seismic faults (thrust or strike-slip) and are associated with the lithospheric convergence (Papazachos, 1990). It should be noticed that due to the lack of data we merge the external seismic sources in order to form larger areas of study called seismic zones. The formation of each seismic zone is based on previous work on seismic zonation of the Aegean and the surrounding area (Papazachos, 1990, 1992; Papazachos and Papaioannou, 1993). Following the aforementioned authors, we provide in Table 1 the composition of each seismic zone regarding the seismic sources forming them. These seismic sources are proposed in Papaioannou and Papazachos (2000). The dataset used in this study is based on the updated and extended earthquake catalog for Greece and the adjacent areas by Makropoulos et al. (2012) (http://www.nat-hazards-earth-syst-sci.net/12/1425/2012/nhess-12-1425-2012-supplement.zip — last accessed July 2012) and concerns shallow earthquakes with focal depth ≤60 km, covering the period 1976–2009 (Fig. 2). Furthermore, using the method introduced by Stepp (1971), Makropoulos et al. (2012) have computed the magnitude of completeness (Mc) of their updated catalog for the period 1976–2009 to be as $Mc = 4.1$.

Moreover, the window method introduced by Gardner and Knopoff (1974) and modified by Uhrhammer (1986), is used in this study for the identification of mainshocks and aftershocks and thus the declustering of the earthquake catalog. This technique considers that for each earthquake with magnitude M, the subsequent shocks are identified as aftershocks, if they occur within a specified time and distance interval (vanStiphout et al., 2012).

3. Theoretical background of the Nonextensive Statistical Physics formalism

Nonextensive Statistical Physics refers to the non-additive entropy Sq (Tsallis, 2009), which is a generalization of Boltzmann–Gibbs (BG) entropy. The non-additive entropy Sq reads as:

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

where k is some conventional positive constant taken to be Boltzmann's constant in thermostatistics, p_i is a set of probabilities, W is the total number of microscopic configurations, and q the entropic index. For

Table 1
The composition of the seismic zones used in this study.

Seismic zones	Seismic sources
1	4,5
2	6,7,8,11
3	9,10,12,13
4	14,15,16,17
5	18,19,20