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Non-extensive statistical physics applied to heat flow and the earthquake frequency–magnitude distribution in Greece

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HIGHLIGHTS

- Seismicity in Greece and its relation to heat flow.
- Seismicity is investigated using the NESP formalism.
- High q_M values are consistent with strong earthquakes.
- The central Aegean region presents high heat flow values.
- Discussion on the dynamical character of the non-extensive parameter.

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ABSTRACT

This study investigates seismicity in Greece and its relation to heat flow, based on the science of complex systems. Greece is characterised by a complex tectonic setting, which is represented mainly by active subduction, lithospheric extension and volcanism. The non-extensive statistical physics formalism is a generalisation of Boltzmann–Gibbs statistical physics and has been successfully used for the analysis of a variety of complex systems, where fractality and long-range interactions are important. Consequently, in this study, the frequency–magnitude distribution analysis was performed in a non-extensive statistical physics context, and the non-extensive parameter, q_M, which is related to the frequency–magnitude distribution, was used as an index of the physical state of the studied area. Examination of the spatial distribution of q_M revealed its relation to the spatial distribution of seismicity during the period 1976–2009. For focal depths $\leq$40 km, we observe that strong earthquakes coincide with high q_M values. In addition, heat flow anomalies in Greece are known to be strongly related to crustal thickness; a thin crust and significant heat flow anomalies characterise the central Aegean region. Moreover, the data studied indicate that high heat flow is consistent with the absence of strong events and consequently with low q_M values (high *b*-values) in the central Aegean region and around the volcanic arc. However, the eastern part of the volcanic arc exhibits strong earthquakes and high q_M values whereas low q_M values are found along the North Aegean Trough and southwest of Crete, despite the fact that strong events are present during the period 1976–2009 in both areas.

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1. Introduction

Greece is characterised by complex tectonic features such as the Hellenic Subduction Zone (HSZ) and the active volcanic arc which is present ∼200 km behind the trench [1] (Fig. 1).

The HSZ is the most seismically active region in Europe and presents a complex geometry expressed as a curved plate boundary [3]. The Kefalonia Transform Zone (KTZ) separates the northern part of the Hellenic subduction boundary from the southern one [2]. Active subduction causes high seismicity at shallow depths, the presence of low-angle thrust faults along the Hellenic arc and intermediate-depth seismicity that forms a well-defined Benioff zone in the southern Aegean [4–6]. The dextral strike-slip motion extending from the North Anatolian Fault (NAF) to the northern Aegean is principally expressed along the North Aegean Trough (NAT) [7].

A previous study by Fytikas and Kolios [8] presented a heat flow map of Greece based on heat flow data that had already been collected in the marine area by other authors [9–11] as well as on their own measurements taken mainly in the continental area. In addition, Kalyoncuoglu et al. [12] studied the spatial variation of *b*-values and heat flow in the Aegean region. The aforementioned authors found that high *b*-value anomalies within Aegean basin, except along the NAT, conform to high heat flow values. However, these authors do not analyse the whole Greek territory and their calculations show consistency between seismicity and the *b*-values in the NAT area for the chosen study period. On the contrary, the present study covers Greece and the adjacent areas and shows inconsistency between the calculated non-extensive index and seismicity in the areas southwest of Crete and along the NAT for the period 1976–2009. These findings are further discussed based on the dynamic character of the calculated non-extensive parameter.

We use the concept of Non-Extensive Statistical Physics (NESP) to study seismicity in Greece by comparing the obtained values of the q_M parameter to heat flow anomalies. This parameter, which is estimated from a novel cumulative magnitude distribution derived from the fragment asperity model [13], can be used as an index of the stability of a seismic area. The fundamental conceptual framework of NESP, which comes from first principles, allows seismologists to characterise the dynamic regime of an active tectonic area.

NESP was proposed by Tsallis [14] and refers to the non-additive entropy S_q which is a generalisation of Boltzmann–Gibbs (BG) statistical physics. Systems, in which the classical BG formula does not keep entropy extensive include those whose elements are strongly correlated. According to the non-extensive formalism [15, and references therein], entropy reads as: $S_q = k(1 - \sum_{i=1}^{W} p_i^q)/(q-1)$, where k is some conventional positive constant taken to be Boltzmann's constant in thermodynamics, p_i is a set of probabilities, W is the total number of microscopic configurations, and q is the entropic index.

We note that NESP formalism has been applied to many non-linear dynamical systems [15] and seems an appropriate framework for the study of complex phenomena in earth sciences. The effectiveness of NESP has been demonstrated in a series of publications on seismicity [16–28], natural hazards [29–31], plate tectonics [32], geomagnetic reversals [33], and rock physics [34–36].

2. Earthquake data

The dataset used in this study is based on the updated and extended earthquake catalogue for Greece and adjacent areas by Makropoulos et al. [37]: http://www.nat-hazards-earth-syst-sci.net/12/1425/2012/nhess-12-1425-2012-supplement.zip — last accessed March 2015. These authors computed that events with moment magnitude (M_w) equal to or above 4.1 ($M_w \geq 4.1$) are completely reported for the period 1976–2009 using the method introduced by Stepp [38]. Therefore, in this study, the threshold magnitude m_0 of the earthquake dataset is considered equal to $m_0 = 4.1$. This corresponds to a total of 4537 events. The epicentral distribution of earthquakes for different depth levels is presented in Fig. 2. It is observed that dense accumulation of seismicity occurs along the HSZ, in mainland Greece and along the NAT.

Earthquake focal depths show that 53.95% of the earthquakes have occurred at depths varying in the range of 0–20 km in the crust (Table 1). It should be mentioned that the vast majority of earthquakes along the NAT occur in this depth range. Furthermore, 23.69% of earthquakes occur in the depth interval of 21–40 km and 14.16% in the interval of 41–60 km. According to Table 1, the number of earthquakes decreases significantly beyond 60 km. Earthquake foci reach a maximum depth of about 180 km under the volcanic arc in the southern Aegean region.

Papazachos et al. [6] showed that the Wadati–Benioff zone, which defines the boundary of the subducting slab, starts at a depth of 20 km under the convex side of the Hellenic arc and dips towards the back-arc area, where it reaches a depth of 150 km or more under the volcanic arc. In general, strong seismic activity is observed along the HSZ while the back-arc region exhibits low seismicity.

3. Heat flow data and crustal thickness

We used heat flow data provided by several studies of the thermal state of the crust in Greece and the surrounding areas [9–11]. Fytikas and Kolios [8] constructed a heat flow map of Greece (Fig. 3) using these data [9–11] as well as additional data of their own [8]. In places where the available heat flow data were not adequate, measurements of surface hydrothermal phenomena (thermal springs, fumaroles and hot grounds) and thermal measurements in drill holes done for geothermal investigations were taken into consideration by Fytikas and Kolios [8] in order to characterise the heat flow pattern and