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Spectral and informational analysis of seismicity: An application to the 1996–2012 seismicity of the Northern Caucasus–Azerbaijan part of the greater Caucasus–Kopet Dag region

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HIGHLIGHTS

- The periodic behaviour of the earthquakes in the Northern Caucasus region is analysed.
- The methods of periodogram, SSA and the Fisher–Shannon method are used.
- Two main significant periodicities are detected at 102 months and 20 months.
- The long-term variation of the seismic series is characterized by higher organization.

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ABSTRACT

The time series analysis of seismic sequences needs proper methodologies that allow us to capture the main features of the time dynamics of earthquakes. Among these features, the identification of periodicities along with the quantification of their intensity represents an important task, concerning the detection of regular dynamical behaviours, with clear implications for earthquake prediction. In the present study, we applied three different methods to investigate the time dynamics of the seismic activity of the Northern Caucasus–Azerbaijan part of the Greater Caucasus–Kopet Dag region. We analysed the monthly number of earthquakes which occurred between 1996 and 2012 by means of: (i) the robust estimation of the periodogram, (ii) the singular spectrum analysis (SSA), and (iii) the Fisher–Shannon method. Two main significant periodicities are detected: 102 months and 20 months. The first corresponds actually to the long-term variation of the monthly seismic activity of the area, while the second represents the more intense cyclic component. Periodicities of 7 and 30 months are also identified, but with a lower intensity than the 20-month periodicity. The Fisher–Shannon method has revealed that the long-term variation of the series is also characterized by higher organization and lower degree of disorder. The present study shows how the application of methods from statistical mechanics could contribute to unveil dynamical features in seismicity.

1. Introduction

To aim at the better comprehension of the temporal dynamics of seismicity has induced researchers to apply methods from statistical mechanics able to reveal some fundamental features of earthquakes. Among these there are the recent

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non-extensive statistical physics and the natural time domain approach that have been revealed to be important for understanding processes occurring in the lithosphere as a complex system [1–5].

For instance, fractal methods based on the concept of self-similarity of a seismic process has implied that the statistics, like the Allan Factor, describing the time properties of a seismic process behaves as a power-law function. The application of multifractal methods became well suited to evidence heterogeneous dynamical behaviours in seismic processes [6], estimating several scaling exponents describing the temporal fluctuations of seismicity at different levels of variations. Such analyses agree that earthquake time dynamics is characterized by intermittent fluctuations with periods of intense seismic activity interspersed with those of low seismicity. Approaches based on the concept of "natural time domain" [7] were used to gain insight into the dynamics of seismicity, where the "natural time" does not involve the interoccurrence times between seismic events. In all the previous methods, the seismic process is represented as a dynamical geophysical phenomenon, whose complexity is described in terms of long-range correlations and clusterization among the events.

Several studies show that oscillating time fluctuations could characterize earthquake temporal distributions [8]. Recently, Metivier et al. [9] found that the phases of the solid Earth tide are significantly correlated with the timing of earthquakes. Actually, such non-tectonic forcings (e.g. lunar and solar tides, ocean waves, seasonal influences, etc.) applied to the fault system are regular and could reasonably justify the presence of periodicities in the time distribution of earthquakes [9].

In the present study, applying robust statistical methods we aim at investigating the time dynamics of the earthquake series of a seismic area of the Caucasus, revealing in particular the presence of periodic components in the monthly seismic activity.

2. Methods

2.1. The periodogram analysis

Periodicities are maybe the first type of time fluctuations that need to be revealed and analysed when one approaches the study of a natural phenomenon. Observational data are generally characterized by noise, uneven sampling, spikes, and sometimes they are very short; therefore, efficient algorithms are necessary to get as much information as possible.

The task of periodicity identification in time series can be considered as a decision problem based on spectral analysis. Wichert et al. [10] introduced a formal statistical testing procedure for the detection of periodicities, based on the so-called Fisher's g-statistic for which the exact null-distribution can be derived under the Gaussian noise assumption.

Consider the following simple model of periodic series:

$$y_n = \beta \cos(\omega t + \phi) + \varepsilon_n \tag{1}$$

where β is a positive constant, $0 < \omega < \pi$, ϕ uniformly distributed in $(-\pi, \pi]$, and $\{\varepsilon_n\}$ is a sequence of uncorrelated random variables with mean 0 and variance σ^2, independent of ϕ.

Then, the classical periodogram is given by the following formula:

$$I(\omega) = \frac{1}{N}\left|\sum_{n=1}^{N} y_n \mathrm{e}^{-\mathrm{i}\omega n}\right|^2, \quad 0 \le \omega \le \pi \tag{2}$$

where N is the length of the time series. The periodogram is further evaluated at normalized frequencies

$$\omega_l = \frac{2\pi l}{N}, \quad l = 0, 1, \ldots, a \tag{3}$$

where $a = [(N-1)/2]$ and $[x]$ indicates the integer part of x. If the signal has a significant sinusoidal component with frequency ω_0, then the periodogram has a high probability to exhibit a peak centred at that frequency. While, if the time series is a purely random process, which means $\beta = 0$ in Eq. (1), then the periodogram is uniform appearing flat for any frequency bands [11].

To test for the main periodicity (as argued by the highest peak in the periodogram), the g-statistic is used

$$g = \frac{\max\limits_{1\le l\le a} I(\omega_l)}{\sum\limits_{l=1}^{a} I(\omega_l)}, \tag{4}$$

which is the maximum periodogram ordinate divided by the sum of all periodogram ordinates for $l = 1, \ldots, a$. A large value of g indicates a strong periodic component and leads to the rejection of the null hypothesis.

Wichert et al. [10] calculated the exact p-value for a realization of the g-statistic, under the Gaussian noise assumption

$$P(g > x) = a(1-x)^{a-1} - \frac{a(a-1)}{2}(1-2x)^{a-1} + \cdots + (-1)^b \frac{a!}{b!(a-b)!}(1-bx)^{a-1} \tag{5}$$

where b is the largest integer less than $1/x$ and x is the observed value of the g-statistic. Eq. (5), then, provides the exact significance value for a realization of the g-statistic under the assumption of Gaussian distribution of the noise.