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Temporal distribution of recorded magnitudes in Serbia earthquake catalog

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ABSTRACT

We focus on earthquakes that were recorded in Serbia between 1970 and 2011 within shallow parts of the Earth's crust, having local magnitudes from the 1.2–5.8 interval. The main goal of the performed analysis is to examine whether the temporal sequence of these recorded magnitudes exhibits some deterministic pattern or whether it simply represents a series of random events. For this purpose, the temporal distribution of earthquake magnitudes above the magnitude of completeness is analyzed by means of nonlinear time series analysis and surrogate data testing, as well as by means of the autocorrelation function. Piece-wise low cross-prediction errors, with 75% of segment pairs having the error smaller than its average value, indicate stationary properties of the examined sequence. Results of surrogate data testing indicate high zeroth-order prediction error that is independent of prediction time for the original dataset and 20 different surrogates, implying that the observed magnitude sequence is a series of independent random events drawn from some fixed but unknown distribution. These findings are supported further by a low value of the determinism factor for an earthquake treated as a system with four degrees of freedom (epicentral latitude and longitude, hypocentral depth and magnitude). The randomness in observed data is indicated further by the properties of the autocorrelation function, whose values for different time lags fall within the 95% confidence limit without an apparent pattern.

1. Introduction

Basic statistical properties of seismicity are implied by a special temporal pattern of earthquake occurrence along a single fault or a fault segment (i.e. recurrent events) and by spatial and temporal distribution of earthquakes recorded in one tectonic (seismic) area (i.e. interoccurrent events), which are typically examined by analyzing the corresponding earthquake catalogs [1]. Extensive seismological studies of these seismic databases have shown that temporal distribution of earthquakes in one region usually follows a discrete Poisson distribution, indicating temporal independence of the recorded seismic events [2,3]. This time-independent occurrence is a prominent feature of large earthquakes, which are assumed to occur

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as a stationary Poisson process inside a specific region [4–7]. Besides the assumption of Poisson distribution, some authors also propose non-Poisson models, which are more consistent with underlying physics and take into account the occurrence history, like Markov processes [8]. Another frequent hypothesis on temporal seismic distribution relies on the assumption that magnitudes of all the seismic events (including large events, foreshocks and aftershocks) are independent random variables, which is the main starting point of a widely used epidemic-type aftershock sequence (ETAS) model. This ETAS model describes the space–time magnitude distribution of earthquake occurrences, by presuming that the squared distance between an aftershock and its triggering event follows a Pareto distribution [9]. Following the same assumption of earthquakes as random events, Ben-Naim et al. [10] showed that the series of recorded earthquakes is consistent with a random process for magnitudes in the range $M \in [7.0, 8.3]$.

In contrast to aforementioned models of earthquakes as predominantly independent events, there are certain claims of periodic, quasi-periodic and chaotic temporal distribution of recorded earthquakes, as a result of extensive analyses in the area of nonlinear dynamics and chaos theory [11,12]. Supporting this point of view, Beltrami and Mareshal [13] tried to reconstruct the strange attractor for the earthquake time series recorded in the Parkfield seismic region between 1969 and 1987. They came to ambiguous results – either this series cannot be distinguished from a random one, or it has a strange attractor with dimension higher than 12. Matcharashvili et al. [14] found evidence of low-dimensional attractor for earthquakes in Caucasian region by using the inter-event times between successive events. Tiwari et al. [15] applied a nonlinear forecasting approach in a reconstructed phase space of earthquake frequency in the Central Himalayan Region. Results of their studies indicated a low positive correlation between predicted and observed data suggesting that the earthquake dynamics in this area is characterized by a mix of stochastic and chaotic behavior.

Having in mind these previous divergent evidences and assertions on temporal distribution of seismic events, we apply a series of tests in order to examine whether there is some underlying pattern of temporal distribution of earthquake magnitudes recorded in Serbia, between 1970 and 2011. The research is done by applying the methods of nonlinear time series analysis [16], which were previously rarely used in the field of seismology [17], even though they were successfully applied in many other fields of geophysics [18,19].

The scheme of the paper is as follows. Seismic activity in Serbia is described in Section 2, while the applied methods are detailed in Section 3. The obtained results are presented in Section 4, while in the last section we give a brief discussion on the applied methods and obtained results, with suggestions for further research.

2. Seismic activity in Serbia

According to Advanced National Seismic System composite earthquake catalog (ANSS), hosted by Northern California Earthquake Data Center [20], 757 earthquakes of local magnitudes $M_L \in [1.2, 5.8]$ were recorded in Serbia between 1970 and 2011 (Fig. 1). In this period only four moderate earthquakes of local magnitudes $M_L \in [5.2, 5.8]$ were recorded, with epicenters located at a wider area of Kopaonik, Mionica, Trstenik and Kraljevo. One could note from Fig. 1 that the major seismic activity in this period was caused by the fault motion in west/northwest-east/southeast direction, due to compression along the contact of Adriatic table and Dinarides, on one hand, and extension generated by the regressive roll-back of the subducted lithosphere in Carpathian zone, on the other hand [21,22]. Majority of earthquakes in this period was recorded during 2002 (Fig. 2) with most frequent magnitude of 2.7 (Fig. 3a). Hypocentral depth was less than 40 km, with the most frequent value of 10 km, implying that only shallow seismic events were registered in the observed period (Fig. 3b).

3. Applied methods

In present paper, we analyze temporal distribution of earthquake magnitudes recorded in Serbia between 1970 and 2011, because there are no instrumental recordings of earthquakes before 1970. Since the observed seismic data set contains many earthquakes with magnitude under the completeness of the catalog, it means that the corresponding analysis would be missing many low magnitude earthquakes, which could likely affect the results. In other words, a first and compulsory step in our analysis would be to calculate a magnitude of completeness M_c, as the lowest magnitude at which 100% of the earthquakes in a space–time volume are detected [23]. In present paper, magnitude of completeness was calculated in ZMAP software [24], by applying Maximal Curvature technique, as a catalog-based method to assess M_c. This technique represents fast and straightforward way to estimate M_c and consists in defining the point of the maximum curvature by computing the maximum value of the first derivative of the frequency-magnitude curve. The advantages of applying this technique are its easy applicability and the fact that it requires fewer events than other techniques to reach a stable result [25].

After determining the magnitude of completeness, a series of main shocks, without foreshocks and aftershocks, with local magnitude equal or larger than M_c is examined by the means of nonlinear time series analysis. In order to conduct this analysis, we had to embed the observed scalar series into the appropriate phase space via the Takens embedding procedure [26] by using the open-source software [27]. The optimal embedding delay is calculated using average mutual information method [28], while the minimum embedding dimension is examined by the method of false nearest neighbors [29], considering that two points are false neighbors if the normalized distance between their embedding coordinates is larger than a given threshold (R_{tr}). According to [29], the value of $R_{tr} = 10$ proves to be a good choice for most data sets.