Annuaire de l'Universite de Sofia "St. Kliment Ohridski", Faculte de Physique, v. 103, 2010

LONG-TERM CORRELATIONS IN BULGARIAN SEISMIC DATA

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Милен Цеков, Валентина Христова. ДАЛЕЧНИ КОРЕЛАЦИИ В СЕИЗМИЧНИ ДАННИ ОТ БЪЛГАРИЯ

В настоящата работа се разглеждат далечните корелации във времеви редове от сеизмични данни, характеризиращи сеизмичността в България. Ние изследваме времевите интервали между последователни земетресения с магнитуд, по-голям от определена прагова стойност, извлечени от два сеизмични каталога: (1) Каталог на земетресенията в България за периода 1981−1990 г., публикуван от Българската академия на науките, и (2) данни за български земетресения в периода 1991−2009 г., съдържащи се в каталога на Националния информационен сеизмичен център (NEIC) на САЩ. За да оценим далечните корелации в изследваните времеви редове, ние прилагаме метода Detrended Fluctuation Analysis (DFA). И за двата каталога откриваме наличие на далечни корелации със скейлингов показател $\alpha > 0.5$, което показва наличието на статистическа памет и persistence. Откриваме, че скейлинговото поведение на интервалите между две последователни земетресения не е инвариантно във времето. В частност установяваме, че в определени времеви интервали стойността на скейлинговия показател α нараства с нарастването на праговия магнитуд, докато за други времеви интервали стойността на скейлинговия показател α не се мени значимо или се увеличава слабо с увеличаване на праговия магнитуд в рамките на изследвания диапазон от прагови магнитуди, вариращи от $M = 2.8$ до $M = 3.3$. Показваме, че систематични трендове в броя на неотчетените слаби сеизмични събития в земетръсните каталози водят до специфично поведение на скейлинговите криви, характеризиращо се с появата на crossover-и в тях.

Milen Tsekov, Valentina Hristova. LONG-TERM CORRELATIONS IN BULGARIAN SEISMIC DATA

We analyze long-term temporal correlation properties of interoccurrence times between earthquakes derived from two earthquake catalogues characterizing Bulgarian seismicity: (1) Bulgaria catalogue of earthquakes over the time period 1981-1990 published by the Bulgarian Academy of Sciences, and (2) the catalogue of the USA National Earthquake Information Center (NEIC) for

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earthquakes after 1990. We apply the Detrended Fluctuation Analysis (DFA) method to quantify long-term correlations in the data. For both catalogues we find evidence for long-term power-law correlations with scaling exponent $\alpha > 0.5$ indicating long-term memory and positive persistence. We also find that the scaling properties of the interoccurrence intervals are not temporally invariant but change with time. Specifically, for certain time periods we observe threshold magnitude dependence of the scaling exponent with tendency toward randomness for larger threshold magnitudes while for other time periods we do not observe significant change in the long-term correlation properties of the records over the range of threshold magnitudes from $M = 2.8$ to $M = 3.3$ or we even observe a slight increase of the persistence over the considered range of threshold magnitudes. We also demonstrate that systematic trends in the number of missed weak and moderate seismic events lead to a specific crossover behavior of the fluctuations of interoccurrence intervals.

Keywords: long-term correlations, seismic data
PACS numbers: 91.30.Ab, 89.75.Da, 95.75.wx

1. INTRODUCTION

Understanding the complex spatio-temporal distribution of earthquakes and the mechanisms governing this behavior is one of the major challenges of today seismology. One of the open questions related to the temporal earthquake behavior is whether the interoccurrence times between earthquakes are long-term correlated or result from a memoryless process. The answer to this question is of great importance for seismotectonics, for estimation of seismic hazard, and for earthquake prediction. However, the quantification of long-term correlation properties of earthquake interoccurrence time series is hampered by the quality of earthquake data. On one hand, comprehensive data for low-magnitude earthquakes are available only for the last several decades. On the other hand, reliable data for strong earthquakes exist for more than a century. However, typical time periods between successive strong earthquakes in a given region are of the order of decades and even centuries. Thus, seismic time series for both strong and weak earthquakes are relatively short. Moreover, earthquake time series are typically nonstationary. Also, uncertainties in the computation of magnitudes of earthquakes introduce noise in the time series of interoccurrence times between successive earthquakes with magnitudes larger than a given threshold value. Thus, earthquake interoccurrence intervals time series are typically nonstationary, noisy and on many occasions short which seriously hampers reliable estimation of their long-term correlation properties.

In the recent years, following the development of robust methods for quantification of long-term correlations in short and nonstationary data [1], much interest has been attracted to the scaling properties of earthquake interoccurrence intervals data [2-9]. Lana et al. [2] studied the fractal behavior of the seismicity in the Southern Iberian Peninsula and found evidence of threshold magnitude dependent persistence of the elapsed times between successive earthquakes, with a tendency toward randomness when the threshold magnitude increases from 2.5 to 4. Livina et al. [3-4] found strong statistical dependence between consecutive recurrence time intervals between earthquakes which is possibly related to long-term persistence in the earthquake occurrences. Lennartz et al. [5] demonstrated presence of persistent power-law correlations in Northern and Southern California seismicity data. Telesca et al. [6] studied the spatio-temporal behavior of the Southern California seismicity over the time period 1981−1998 and found evidence of threshold magnitude dependent persistence in the data with the scaling exponent characterizing persistence decreasing from $\alpha = 1.1$ (indicating strong persistence) for threshold magnitude $M = 2.5$ to $\alpha = 0.6$ (indicating weak persistence) for threshold magnitude $M = 3.7$. Same authors [7] studied the scaling behavior of Central Italy seismicity over the time period 1981−2007 and found evidence of persistence as well as complex space-magnitude dependence of the scaling exponent characterizing persistence which is varying not only with the threshold magnitude but also with the area over which earthquakes is considered. Xu and Burton [8] analyzed the scaling properties of an earthquake catalogue for Greece and found that elapsed time between successive earthquakes possess long memory. However, for the sub-zones of the Hellenic Arc and the Gulf of Corinth they found uncorrelated random behavior instead of memory, thus demonstrating the spatial dependence in the scaling properties of elapsed time between earthquakes. Enescu et al. [9] studied the scaling properties of an earthquake catalogue for Vrancea, Romania and found no significant temporal correlations in the interoccurrence intervals.

Thus, the findings of various authors for seismicity records from different parts of the world are still controversial. For some regions there are strong evidence for long memory and persistent behavior of elapsed time between earthquakes while the seismicity in other regions is memoryless and random. Further analysis of more earthquake time series is required to clarify the details of the spatio-temporal variability in the long-term correlation properties of interoccurrence times between successive earthquakes. In this study we analyze long-term temporal correlation properties of two earthquake catalogues characterizing Bulgarian seismicity: (1) Earthquake catalogue for Bulgaria over the time period 1981−1990 published by the Bulgarian Academy of Sciences [10], and (2) the catalogue of the USA National Earthquake Information Center (NEIC) for earthquakes after 1990. We apply the Detrended Fluctuation Analysis (DFA) method [1] to quantify long-term correlations in the data. For both catalogues we find evidence of long-term power-law correlations with scaling exponent $\alpha > 0.5$ indicating long-term memory and positive persistence. We also find that the scaling properties of the interoccurrence intervals are not temporally invariant but change with time. Specifically, for certain time periods we observe threshold magnitude dependence of the scaling exponent with tendency toward randomness for larger threshold magnitudes while for other time periods we do not observe significant change in the long-term correlation properties of the records over the range of threshold magnitudes from $M = 2.8$ to $M = 3.3$ or we even observe a slight increase of the persistence over the considered range of threshold magnitudes. We also demonstrate that systematic trends in the number of missed weak and moderate seismic events may lead to a specific crossover behavior of the fluctuations of interoccurrence intervals.

The outline of the paper is as follows. In Section 2 we describe the data and we review the method of analysis. In Section 3 we present and discuss the results. Finally, in Section 4 we summarize our findings.

2. DATA AND METHOD

In this paper we study the long-term correlation properties of time series of interoccurrence times between successive earthquakes included in two earthquake catalogues. We first consider the Earthquake catalogue for Bulgaria over the time period 1981-1990 (further BGCAT1981-1990), published by the Bulgarian Academy of Sciences [10] which includes 161 earthquakes of magnitude $M > 3.0$ recorded by the National Operative Telemetric System for Earthquake Information (NOTSSI) on the territory of Bulgaria and border-line regions (up to 10 km) over the time period 1981-1990. Figure 1 shows the interoccurrence times between events with magnitudes greater than a given threshold magnitude M_{TH}. The number of interoccurrence intervals decreases and their average length increases with the increase of M_{TH}. Authors of the catalogue claim that it includes all events of magnitude $M > 3.0$ for the considered time period [10]. This claim is supported by the assessment of the magnitude of completeness of the catalogue using the Gutenberg-Richter cumulative frequency-magnitude law, i.e., $\log N_c(M) = a - bM$, where $N_c(M)$ counts the number of earthquakes with magnitude greater than or equal to magnitude M, and a and b are seismicity and zone-dependent constants (Figure 2). Magnitude of completeness of the catalogue is the magnitude at which the Gutenberg-Richter relation deviates from linearity towards lower magnitudes. In Figure 2 we do not observe such deviation down to the lowest available time scales, i.e., the catalogue may be considered to be complete down to $M = 3.0$.

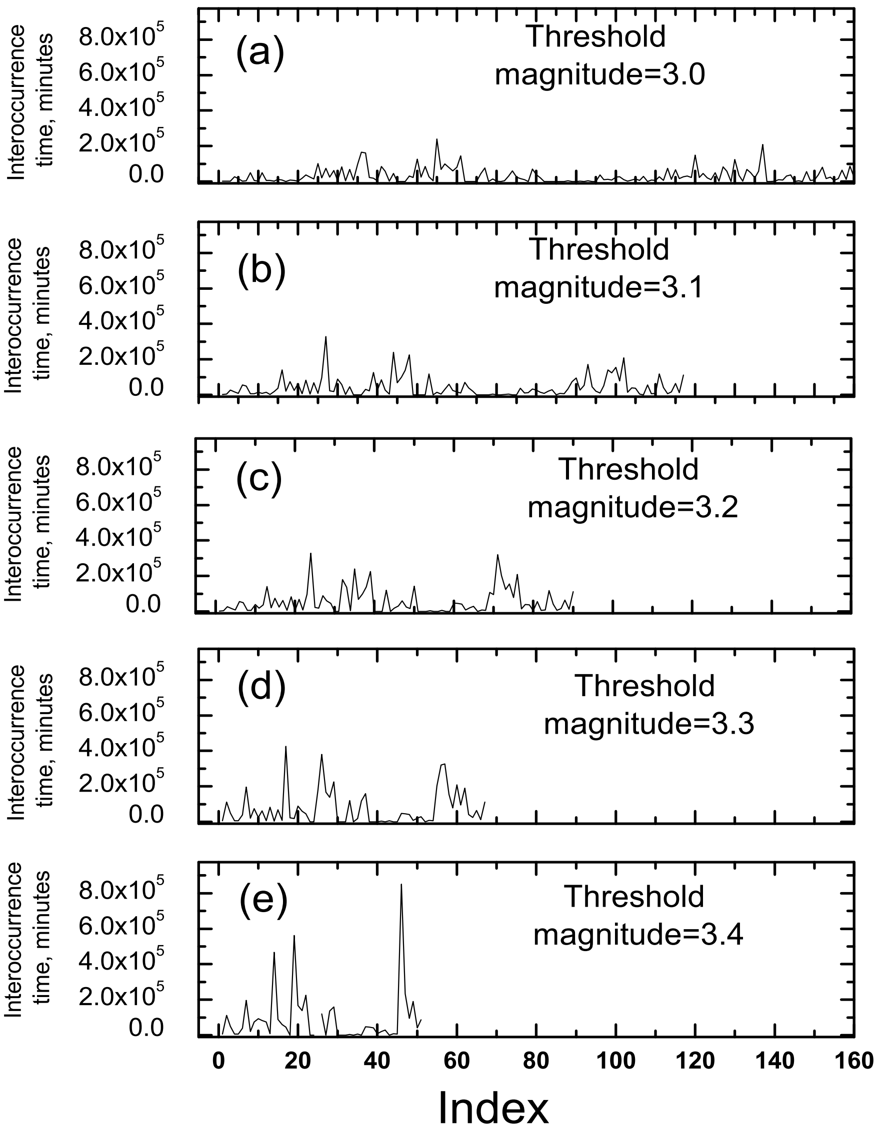

Fig. 1. Interoccurrence time τ_i between earthquakes with magnitude: (a) $M \geq 3.0$; (b) $M \geq 3.1$; (c) $M \geq 3.2$; (d) $M \geq 3.3$; and (e) $M \geq 3.4$ from the BGCAT, 1981-1990 catalogue

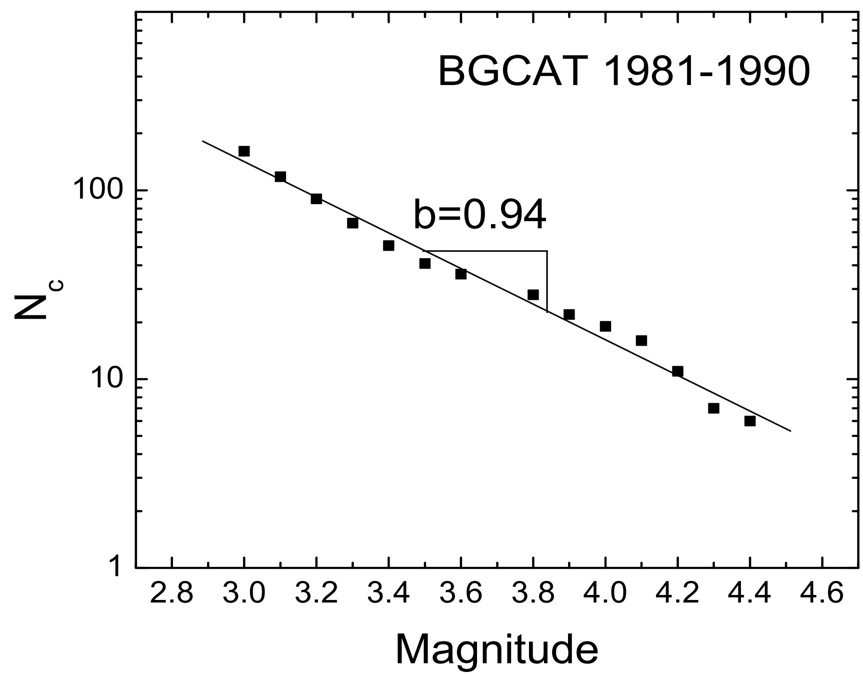

Fig. 2. Catalogue completeness: Gutenberg-Richter cumulative frequency-magnitude plot for the BGCAT1981-1990 catalogue. The plot does not deviate from linearity toward smaller magnitudes indicating that the catalogue is complete down to $M_{TH} = 3.0$. The b-value of the catalogue is 0.94 ± 0.04

Next, we consider data from the worldwide catalogue of the USA National Earthquake Information Center (NEIC) [11]. We select from this catalogue all events with magnitude $M \geq 1.0$ occurring over the time period 1974-2009 in the rectangular area with latitude interval 41.0N-45.0N and longitude interval 22.0E-29.0E, covering Bulgaria and border regions. The number of events in this selection is 1743. Figure 3 shows the interoccurrence times between events from the NEIC catalogue with magnitudes greater than a given threshold magnitude. Over the time period 1974-1990 the mean value of the observed interoccurrence intervals (segment A in Fig. 3a) is larger than the mean value of the interoccurrence intervals for later time periods.

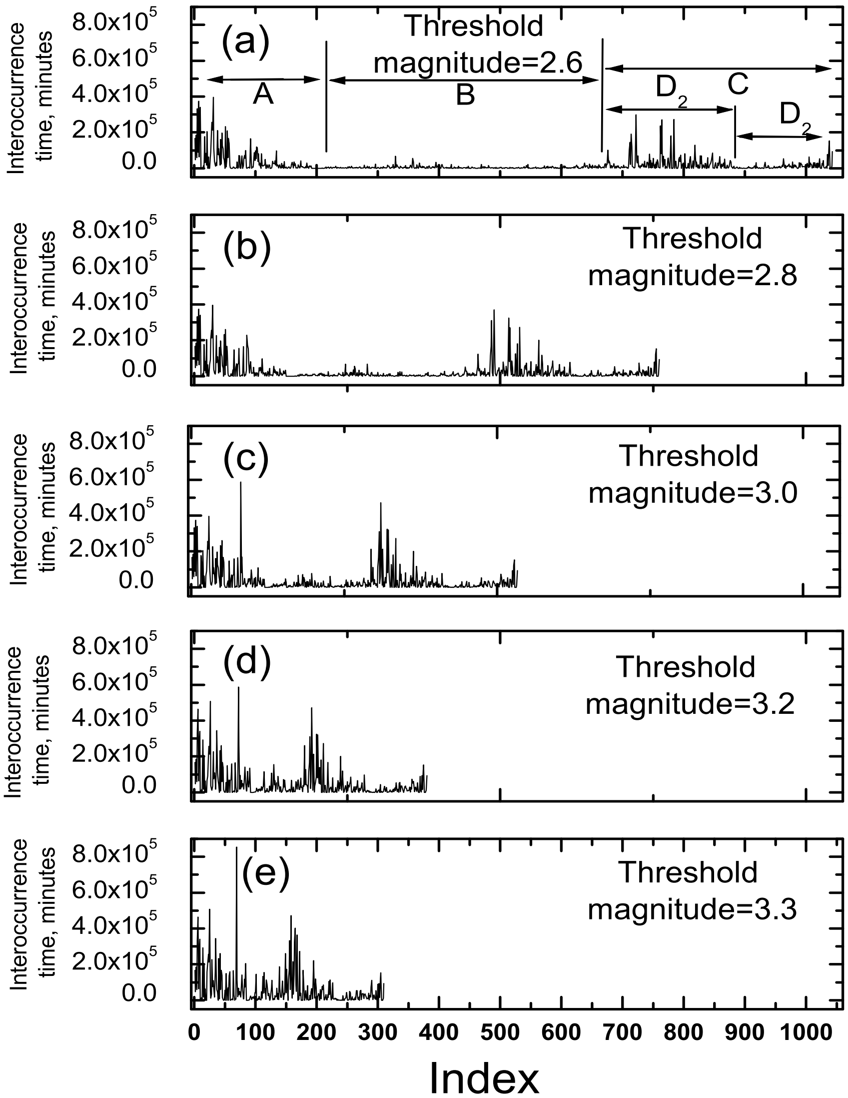

Fig. 3. Interoccurrence time τ_i between earthquakes with magnitude: (a) $M \geq 2.6$; (b) $M \geq 2.8$; (c) $M \geq 3.0$; (d) $M \geq 3.2$; (e) $M \geq 3.3$ from the NEIC catalogue, 1974-2009. Presented are inter-occurrence intervals for 1045 earthquakes with magnitude $M \geq 2.6$ over the time period 1974-2009

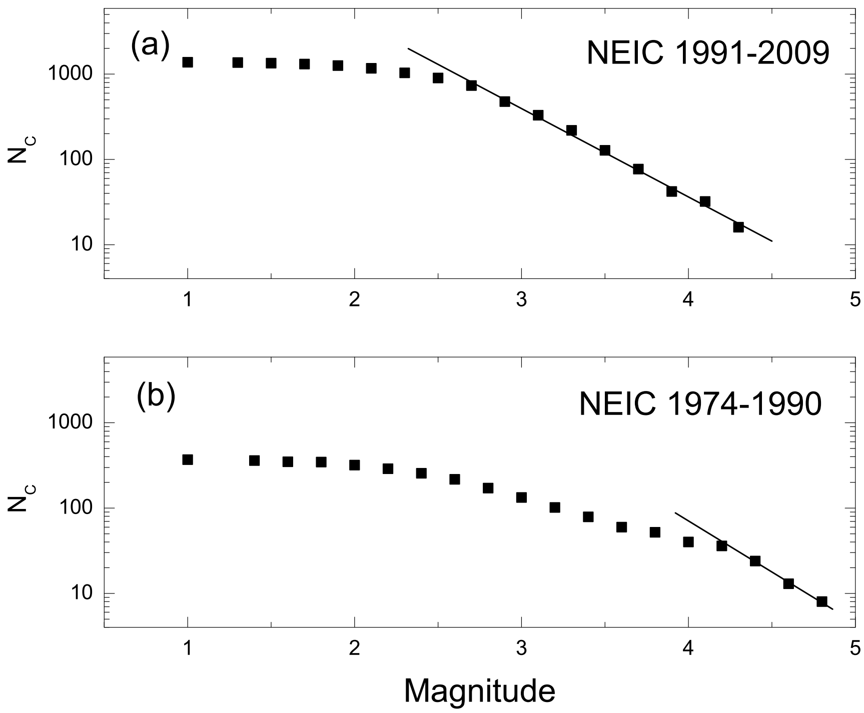

Fig. 4. Catalogue completeness: Gutenberg-Richter cumulative frequency – magnitude plot for the NEIC catalogue over the time periods (a) 1991-2009 and (b) 1974-1990. The plots deviate from linearity toward smaller magnitudes at $M_{TH} = 2.7$ for (a), and at $M_{TH} = 4.2$ for (b) indicating that the catalogue is complete above threshold magnitude $M_{TH} = 2.7$ over the time period 1991-2009 and above threshold magnitude $M_{TH} = 4.2$ over the time period 1974-1990

Our suspicion that the large interoccurrence intervals over the time period 1974-1990 are related to missing events in the NEIC catalogue during this time period is confirmed by the assessment of the magnitudes of completeness for two segments of the catalogue (Fig. 4). Our results show that the catalogue may be considered complete down to threshold magnitude $M = 2.7$ over the time period

1991-2009, but it is complete only down to threshold magnitude $M = 4.2$ over the time period 1974-1990. Consequently, to quantify long-term correlations over the time period 1974-1990 we may use only earthquakes with magnitude $M \geq 4.2$. However, the number of events with magnitude $M \geq 4.2$ in the catalogue over the entire period 1974-2009 is 62. This number is insufficient for quantification of long-term power-law correlations. Thus, we should discard all events from the NEIC catalogue prior to 1991 as well as the events with magnitude $M < 2.7$ over the period 1991-2009. We follow even more conservative approach and consider only events with magnitude $M \geq 2.8$ (higher than the estimated magnitude of completeness $M = 2.7$ of the catalogue over the time period 1991-2009) thus ensuring very low number of missing events for the considered time period and magnitude range. Thus, we perform our analysis only for earthquakes with magnitude $M \geq 2.8$ and over the time period 1991-2009. The number of such events in the NEIC catalogue is 589.

To quantify long-term correlations in earthquake interoccurrence time series we apply the DFA method [1] which consists of the following steps: (i) we first integrate the time series of interoccurrence intervals τ_i to construct the profile $Y(k) = \sum_{i=1}^{k} (\tau_i - \langle \tau \rangle)$, where $\langle \tau \rangle$ is the mean value of the interoccurrence intervals over the period we consider; (ii) we partition the profile $\mathrm{Y(k)}$ into consecutive segments of length s and fit the local trend in each segment with a least-squares polynomial fit; (iii) we then detrend the profile $\mathrm{Y(k)}$ by subtracting the local polynomial trend in each segment of length s, and we calculate the root mean square fluctuation $F(s)$ for the detrended profile. For order-l DFA (DFA-1 if $\mathrm{l} = 1$, DFA-2 if $\mathrm{l} = 2$, etc.) a polynomial function of order l is applied for the fitting of the local trend in each segment of the profile $\mathrm{Y(k)}$; (iv) this procedure is repeated for different scales s. A power-law relation $F(s) \propto s^{\alpha}$ indicates presence of scaling in the studied time series. Thus the fluctuations in τ_i can be characterized by the scaling exponent α, a self-similarity parameter that quantifies the fractal power-law correlation properties of the signal. To ensure sufficient statistics when calculating $F(s)$ for large box sizes s, and thus a more accurate estimate of the scaling exponent α at large time scales, we choose the maximum box size to be $s = N/4$, where N is the length of the time series. To increase additionally the statistics at large time scales we apply "sliding window" version of DFA removing the polynomial trend in each overlapping window.

The scaling exponent α is related to the autocorrelation function exponent γ ($C(s) \propto s^{-\gamma}$ when $0 < \gamma < 1$) and to the power spectrum exponent β

($S(f) \propto 1/f^{\beta}$) by $\alpha = 1 - \gamma/2 = (\beta - 1)/2$. A value of $\alpha = 0.5$ indicates that there are no correlations and the signal is uncorrelated (white noise). If $\alpha < 0.5$ the signal is said to be *anti-correlated*, meaning that large values are more likely to be followed by small values and small values are more likely to be followed by large values. If $\alpha > 0.5$ the signal is correlated and exhibits persistent behavior, meaning that large values are more likely to be followed by large values and small values are more likely to be followed by small values. The higher the value of α, the stronger the correlations in the signal.

3. RESULTS AND DISCUSSION

In Figure 5 we show the results of our scaling analysis for BGCAT1981-1990, obtained using the FDA-1 and DFA-2 methods. On double logarithmic plot we present the dependence of the fluctuation function $F(s)$ on the time scale s. In the presence of power-law correlations in the interoccurrence intervals $\log F(s)$ will increase linearly with $\log(s)$ where the slope is the scaling exponent α. DFA-1, DFA-2, and DFA-3 estimate the correlations in the fluctuations of the interoccurrence intervals by removing constant, linear and quadratic trends respectively.

Our results show that the time series of interoccurrence intervals exhibit positive long-term correlations. For both DFA-1 and DFA-2 and for all threshold magnitudes the scaling exponent $\alpha \approx 0.75$ indicating threshold independent and strong persistence. For threshold magnitude $M = 3.2$ both the DFA-1 and DFA-2 scaling curves bend up at large time scales, which can be interpreted as presence of nonlinear trends in the data [12].

In Figure 6 we show the results of our analysis for the NEIC catalogue, 1991-2009, obtained using the DFA-1 and DFA-2 methods. The number of earthquakes over the period 1991-2009 included in the NEIC catalogue (589 earthquakes with magnitude $M \geq 2.8$ and 219 earthquakes with magnitude $M \geq 3.3$) is much larger than the number of events in the BGCAT1981-1990, which allows us to estimate reliably the long-term correlations for higher threshold magnitudes.

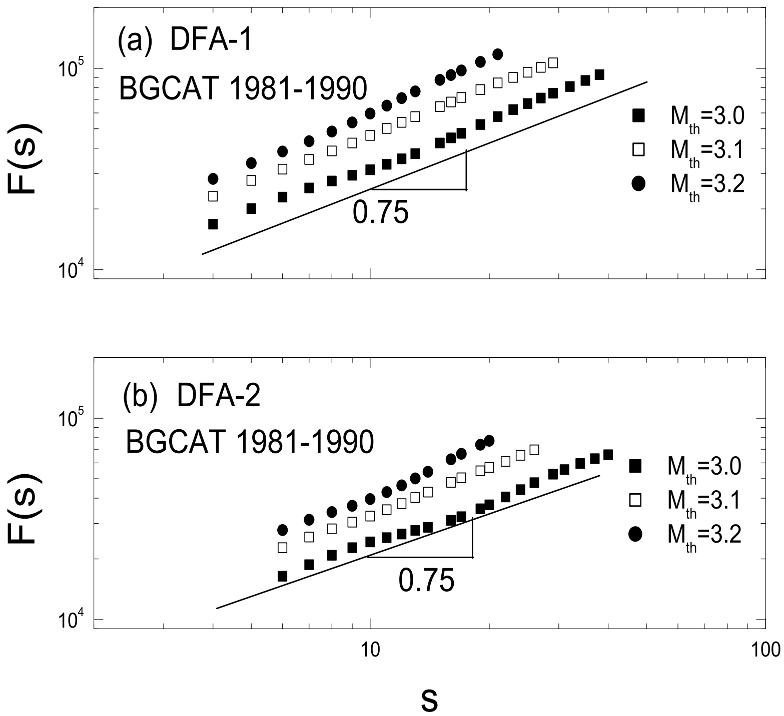

Fig. 5. (a) DFA-1 and (b) DFA-2 analysis of the interoccurrence times of earthquakes from the BGCAT1981-1990 catalogue for $M \geq 3.0$ (filled squares); $M \geq 3.1$ (open squares); and $M \geq 3.2$ (filled circles). Both DFA-1 and DFA-2 show a scaling exponent $\alpha \approx 0.75$ for all threshold magnitudes. The scaling curves for $M \geq 3.2$ bend up at large time scales indicating presence of nonlinear trend in the data

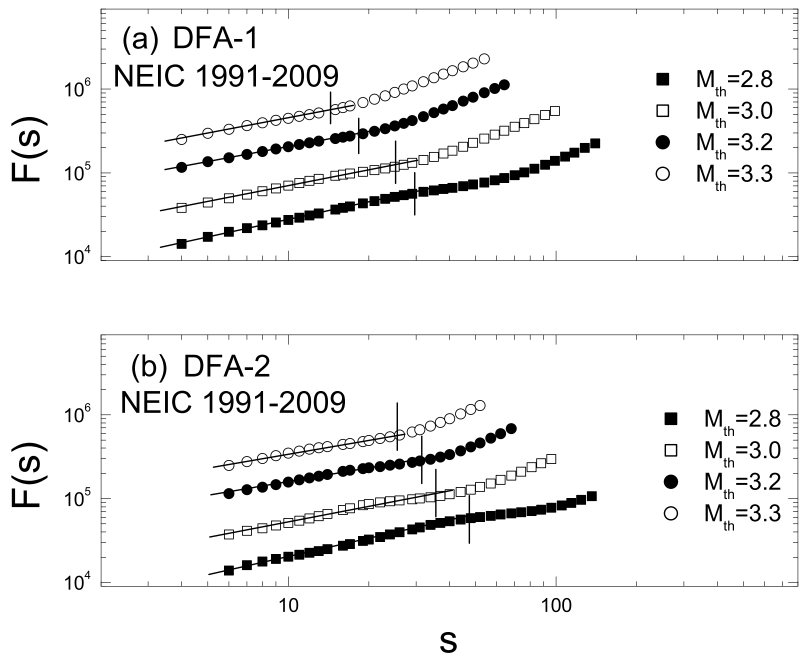

Fig. 6. (a) DFA-1 and (b) DFA-2 analysis of the interoccurrence times of earthquakes from the NEIC catalogue (segment 1991-2009) for $M \geq 2.8$ (filled squares); $M \geq 3.0$ (open squares); $M \geq 3.2$ (filled circles); and $M \geq 3.3$ (open circles). For all threshold magnitudes both the DFA-1 and DFA-2 scaling curves bend up at large time scales indicating presence of nonlinear trends in the data. At low and intermediate time scales the scaling curves exhibit linear increase with a slope $\alpha > 0.5$ indicating positive long-term power-law correlations. The value of the scaling exponent obtained using DFA-1 is $\alpha = 0.69 \pm 0.01$ for $M \geq 2.8$, $\alpha = 0.63 \pm 0.01$ for $M \geq 3.0$, $\alpha = 0.59 \pm 0.01$ for $M \geq 3.2$, and $\alpha = 0.60 \pm 0.01$ for $M \geq 3.3$, while the value of the scaling exponent obtained using DFA-2 is $\alpha = 0.70 \pm 0.01$ for $M \geq 2.8$, $\alpha = 0.63 \pm 0.02$ for $M \geq 3.0$, $\alpha = 0.54 \pm 0.01$ for $M \geq 3.2$, and $\alpha = 0.55 \pm 0.01$ for $M \geq 3.3$. The corresponding slopes are presented by straight lines in the figure

On the other hand, the NEIC catalogue includes events with magnitudes $M < 3.0$ and is complete above threshold magnitude $M_{TH} = 2.7$ which allows us to estimate the long-term correlations for lower threshold magnitudes than we may do it for the BGCAT1981-1990 which includes only events with magnitude $M \geq 3.0$.

For both DFA-1 and DFA-2 and for all threshold magnitudes, on double logarithmic plots the scaling curves exhibit approximately linear increase with the time scale s over short and intermediate time scales while at large time scales all scaling curves bend up indicating presence of nonlinear trends in the data. For all threshold magnitudes we estimate the value of the scaling exponent α over the time scales at which the scaling curves exhibit linear increase and we observe that $\alpha > 0.5$ indicating positive long-term correlations or persistent behavior. Contrary to the BGCAT1981-1990 for which the persistence is independent of the threshold magnitude, in the case of the NEIC catalogue the value of the scaling exponent α depends on the threshold magnitude M_{TH} and it decreases with the increase of M_{TH}. The value of the scaling exponent obtained using DFA-1 is $\alpha = 0.69 \pm 0.01$ for $M \geq 2.8$, $\alpha = 0.63 \pm 0.01$ for $M \geq 3.0$, $\alpha = 0.59 \pm 0.01$ for $M \geq 3.2$, and $\alpha = 0.60 \pm 0.01$ for $M \geq 3.3$, while the value of the scaling exponent obtained using DFA-2 is $\alpha = 0.70 \pm 0.01$ for $M \geq 2.8$, $\alpha = 0.63 \pm 0.02$ for $M \geq 3.0$, $\alpha = 0.54 \pm 0.01$ for $M \geq 3.2$, and $\alpha = 0.55 \pm 0.01$ for $M \geq 3.3$. These estimates show that the fluctuations in the interoccurrence intervals between earthquakes included in the NEIC catalogue exhibit stronger positive long-term correlations for low threshold magnitudes ($M \geq 2.8$) and weaker persistence for large threshold magnitudes ($M \geq 3.2$ and $M \geq 3.3$).

To test whether the obtained scaling properties of the NEIC catalogue are temporally invariant or change with time we divide the catalogue into segments of different length and we estimate the correlations in each segment. First, we divide the NEIC catalogue into two segments. The first segment covers data over the time period 1991-1994 (segment B in Figure 3a), while the second segment includes seismic events from 1995 to 2009 (segment C in Figure 3a). Despite the big difference in the length of the two segments, the number of earthquakes with magnitude $M \geq 2.8$ is approximately equal for both segments (284 events for the time period 1991-1994 and 306 events for the time period 1995-2009) due to the higher frequency of occurrence of earthquakes over the time period 1991-1994. In Figure 7 and Figure 8 we present the results of the DFA-1 and DFA-2 analysis for the corresponding segments. Over the time period 1991-1994 we observe positive persistence for all threshold magnitudes (Figure 7). We also observe that the value of the scaling exponent $\alpha \approx 0.70$ is higher for large threshold magnitudes ($M \geq 3.2$ and $M \geq 3.3$) than the value of the scaling exponent $\alpha \approx 0.60$ for small threshold magnitudes (for $M \geq 2.8$ and $M \geq 3.0$) indicating stronger persistence for larger threshold magnitudes and weaker long-term correlations for smaller threshold magnitudes. We note that over the entire time period 1991-2009 the threshold magnitude dependence is just the opposite, i.e., we observe weaker persistence for larger threshold magnitudes and stronger persistence for smaller threshold magnitudes. However, we also note that over the time period 1991-1994 the number of interoccurrence intervals with magnitude $M \geq 3.2$ and $M \geq 3.3$ are only 77 and 56 respectively. Thus, the estimate of the value of the scaling exponents for the shorter time series over the time period 1991-1994 is less reliable than the estimate obtained for the longer time series including events over the entire time period 1991-2009.

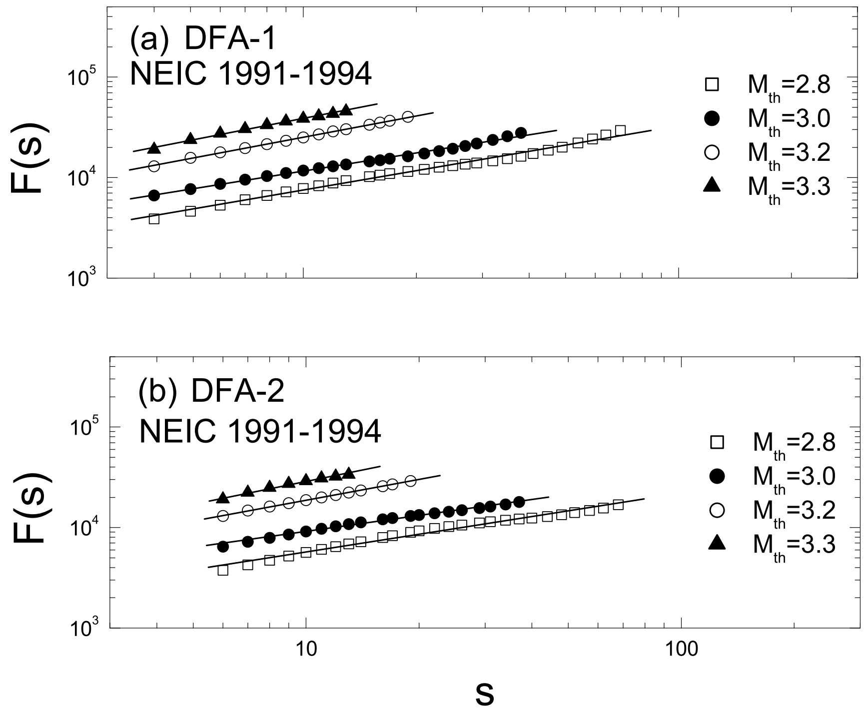

Fig. 7. (a) DFA-1 and (b) DFA-2 analysis of the interoccurrence times of earthquakes from the NEIC catalogue (segment 1991-1994) for $M \geq 2.8$ (open squares); $M \geq 3.0$ (filled circles); $M \geq 3.2$ (open circles); and $M \geq 3.3$ (filled triangles). For all threshold magnitudes the scaling curves exhibit linear increase with a slope $\alpha > 0.5$ indicating positive long-term power-law correlations. The value of the scaling exponent obtained using DFA-1 is $\alpha = 0.64 \pm 0.01$ for $M \geq 2.8$, $\alpha = 0.60 \pm 0.01$ for $M \geq 3.0$, $\alpha = 0.71 \pm 0.01$ for $M \geq 3.2$, and $\alpha = 0.72 \pm 0.02$ for $M \geq 3.3$, while the value of the scaling exponent obtained using DFA-2 is $\alpha = 0.58 \pm 0.02$ for $M \geq 2.8$, $\alpha = 0.54 \pm 0.01$ for $M \geq 3.0$, $\alpha = 0.68 \pm 0.01$ for $M \geq 3.2$, and $\alpha = 0.72 \pm 0.04$ for $M \geq 3.3$. The corresponding slopes are presented by straight lines in the figure

In contrast, the correlation properties of the NEIC catalogue over the time period 1995-2009 differ significantly from the correlation properties over the time period 1991-1994. For the period 1995-2009 we observe positive persistence only on small time scales (Figure 8). At intermediate time scales all scaling curves exhibit a crossover to a region with a slope $\alpha < 0.5$ indicating anti-persistence. The value of the scaling exponent α estimated over the time scales below the crossover scale decreases from $\alpha \approx 0.7$ (indicating strong persistence) obtained for smaller threshold magnitudes ($M_{TH} \geq 2.8$ and $M_{TH} \geq 3.0$) to $\alpha \approx 0.55 - 0.60$ (indicating weak persistence and close to random behavior) for larger threshold magnitudes ($M_{TH} \geq 3.2$ and $M_{TH} \geq 3.3$). The observed decrease of the persistence with increase of the threshold magnitude is in agreement with the observed behavior over the entire time period 1991-2009 and is in contrast to the observed magnitude dependence of the scaling exponent α over the time period 1991-1994.

To study the observed crossover behavior we further divide the segment covering data from 1995 to 2009 into two sub-segments. The first sub-segment covers data over the time period 1995-2005 (segment D_1 in Figure 3a), while the second sub-segment includes data from 2006 to 2009 (segment D_2 in Figure 3a). In Figure 9 and Figure 10 we present the results of the DFA-1 and DFA-2 analysis for the corresponding sub-segments. Over the time period 1995-2005 we observe positive persistence for all threshold magnitudes (Figure 9). The value of the scaling exponent is threshold magnitude dependent and it decreases form $\alpha \approx 0.70$ (indicating strong persistence) obtained for the small threshold magnitude $M_{TH} \geq 2.8$ to $\alpha \approx 0.50 - 0.55$ (indicating weak persistence or close to random behavior) for larger threshold magnitudes $M_{TH} \geq 3.2$ and $M_{TH} \geq 3.3$.

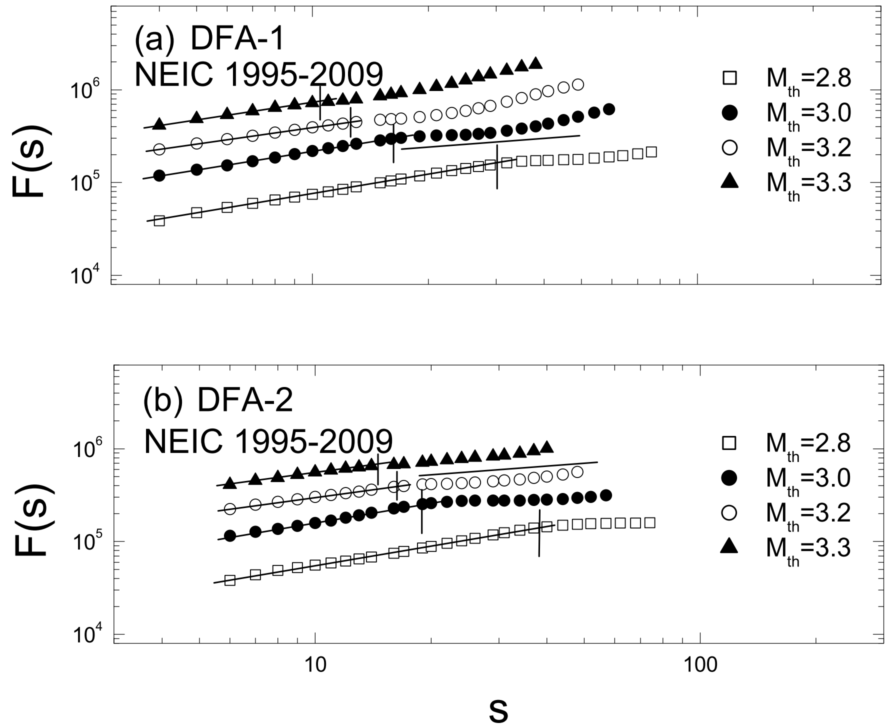

Fig. 8. (a) DFA-1 and (b) DFA-2 analysis of the interoccurrence times of earthquakes from the NEIC catalogue (segment 1995-2009) for $M \geq 2.8$ (open squares); $M \geq 3.0$ (filled circles); $M \geq 3.2$ (open circles); and $M \geq 3.3$ (filled triangles). For all threshold magnitudes and for both DFA-1 and DFA-2 scaling curves we observe a crossover at intermediate time scales. At small time scales (below the crossover scale) we observe linear increase in the scaling with a slope $\alpha > 0.5$ indicating persistence. The value of the scaling exponent in this scaling region obtained using DFA-1 is $\alpha = 0.69 \pm 0.01$ for $M \geq 2.8$, $\alpha = 0.67 \pm 0.01$ for $M \geq 3.0$, $\alpha = 0.58 \pm 0.01$ for $M \geq 3.2$, and $\alpha = 0.59 \pm 0.01$ for $M \geq 3.3$, while the value of the scaling exponent obtained using DFA-2 is $\alpha = 0.70 \pm 0.01$ for $M \geq 2.8$, $\alpha = 0.70 \pm 0.01$ for $M \geq 3.0$, $\alpha = 0.55 \pm 0.01$ for $M \geq 3.2$, and $\alpha = 0.55 \pm 0.01$ for $M \geq 3.3$. The corresponding slopes are presented by straight lines in the figure. At large time scales (above the crossover scale) the slope of all scaling curves is $\alpha < 0.5$ indicating anti-persistence. A straight line with a slope $\alpha = 0.33$ is drawn to guide the eye in this scaling region

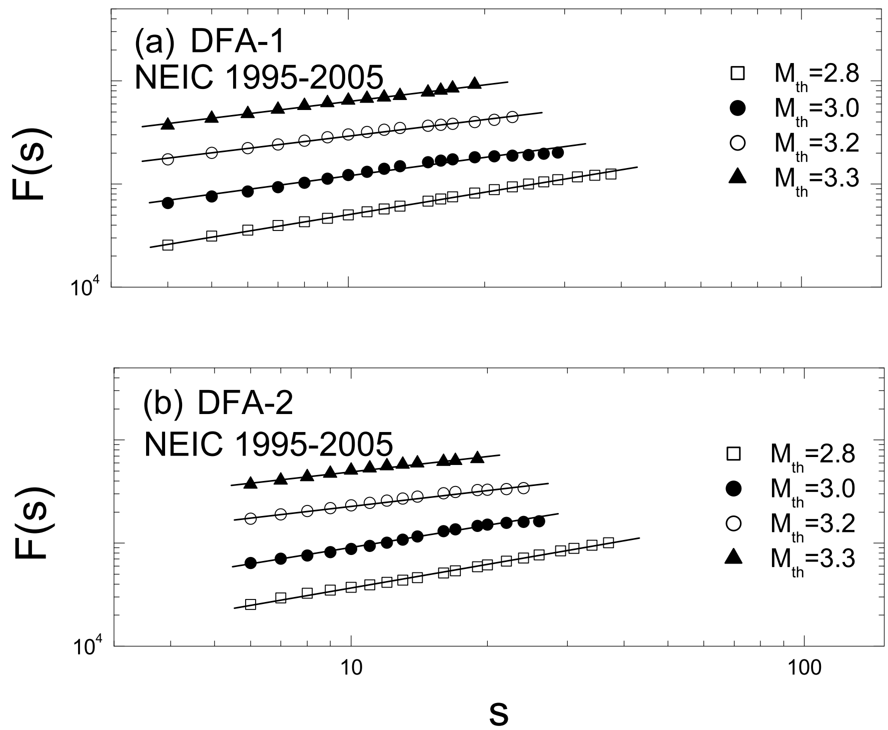

Fig. 9. (a) DFA-1 and (b) DFA-2 analysis of the interoccurrence times of earthquakes from the NEIC catalogue (segment 1995-2005) for $M \geq 2.8$ (open squares); $M \geq 3.0$ (filled circles); $M \geq 3.2$ (open circles); and $M \geq 3.3$ (filled triangles). For all threshold magnitudes we observe a linear increase in both DFA-1 and DFA-2 scaling curves. The value of the scaling exponent obtained using DFA-1 is $\alpha = 0.72 \pm 0.01$ for $M \geq 2.8$, $\alpha = 0.59 \pm 0.02$ for $M \geq 3.0$, $\alpha = 0.53 \pm 0.01$ for $M \geq 3.2$, and $\alpha = 0.55 \pm 0.01$ for $M \geq 3.3$, while the value of the scaling exponent obtained using DFA-2 is $\alpha = 0.75 \pm 0.01$ for $M \geq 2.8$, $\alpha = 0.70 \pm 0.02$ for $M \geq 3.0$, $\alpha = 0.52 \pm 0.02$ for $M \geq 3.2$, and $\alpha = 0.50 \pm 0.02$ for $M \geq 3.3$. The corresponding slopes are presented by straight lines in the figure. The obtained values of the scaling exponent α indicate strong persistence for smaller threshold magnitudes ($M \geq 2.8$ and $M \geq 3.0$) and close to random behavior for larger threshold magnitudes ($M \geq 3.2$ and $M \geq 3.3$)

In contrast, over the time period 2006-2009 we observe crossovers in the scaling curves indicating change in the scaling curve from a region with a slope $\alpha \geq 0.5$ to a region with a slope $\alpha < 0.5$ (Figure 10). We note that the crossover behavior of the scaling curves for the time period 2006-2009 is more pronounced than the analogous crossovers observed for DFA scaling curves for the longer time period 1995-2009. This observation and the lack of crossovers for the other sub-segment covering data for the time period 1995-2005 (Figure 9) demonstrates that the observed crossovers in the scaling curves for the segment covering data from 1995 to 2009 is related to specific scaling properties of the sub-segment of data 2006-2009. Chen et al. [13] have found that occurrence of crossovers in the DFA scaling curves is typical for nonstationary data. Thus, the observed crossover behavior of the DFA scaling curves is probably related to nonstationarities of the time series of interoccurrence intervals over the time period 2006-2009. Close inspection of segment D_2 in Figure 3a (representing the interoccurrence intervals for the time period 2006-2009) shows systematic increase in the length of interoccurrence intervals near the end of the record. This increase most probably is related to missing events at this time period. Most of the events in the catalogue are from the monthly listing of "preliminary" determination of epicenters (PDE). This list is the most complete computation of epicenters and magnitudes done by the United States Geological Survey National Earthquake Information Center (USGS NEIC) and is produced a few months after the events occur [14]. The publication is called "preliminary" because the "final" determination of hypocenters for the world is considered to be the Bulletin of the International Seismological Center (ISC) which is produced about two years after the events occur [14]. The catalogue also includes data from weekly listings and listing of most recent events which are later replaced from the more complete monthly listings when these are available. Thus, the procedure of construction of the catalogue leads to larger number of missing seismic events near the end of the record. Our study of completeness of the catalogue over the sub-periods 2006-2009 and 2008-2009 shows systematic decrease in the quality of the data and systematic increase in the number of missing events near the end of the record (Figure 11). These systematic trends lead to nonstationarities in the data which are responsible for the observed crossover behavior in the DFA scaling curves.

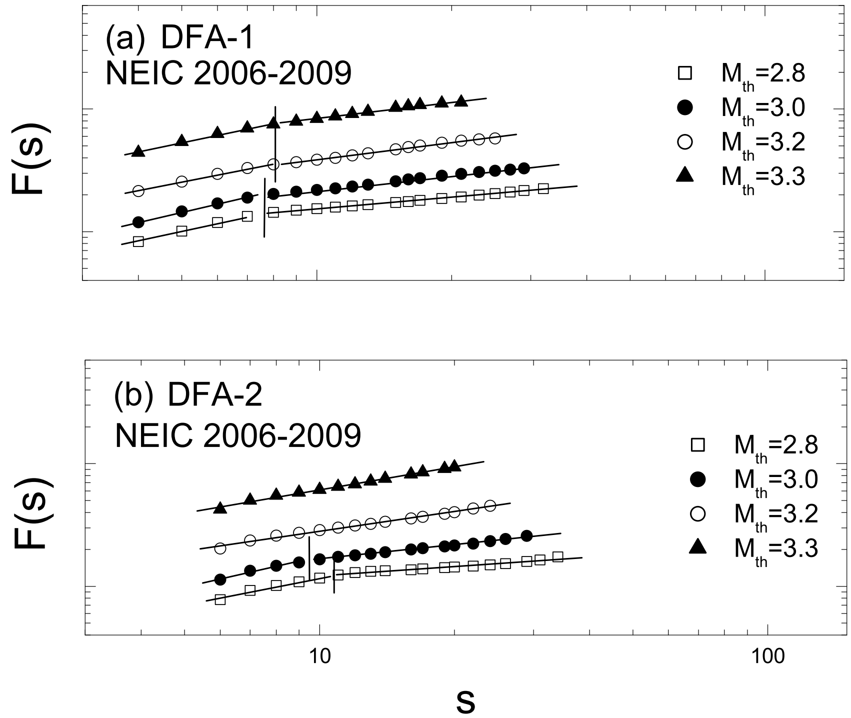

Fig. 10. (a) DFA-1 and (b) DFA-2 analysis of the interoccurrence times of earthquakes from the NEIC catalogue (segment 2006-2009) for $M \geq 2.8$ (open squares); $M \geq 3.0$ (filled circles); $M \geq 3.2$ (open circles); and $M \geq 3.3$ (filled triangles). For all threshold magnitudes we observe a crossover in the DFA-1 scaling curves at intermediate time scales. At small time scales (below the crossover scale) we observe linear increase in the scaling curves with a slope $\alpha > 0.5$ indicating persistence. The value of the scaling exponent obtained using DFA-1 for small time scales is $\alpha = 0.85 \pm 0.02$ for $M \geq 2.8$, $\alpha = 0.83 \pm 0.03$ for $M \geq 3.0$, $\alpha = 0.74 \pm 0.09$ for $M \geq 3.2$, and $\alpha = 0.78 \pm 0.04$ for $M \geq 3.3$, while the value of the scaling exponent obtained using DFA-2 for small time scales is $\alpha = 0.74 \pm 0.05$ for $M \geq 2.8$, and $\alpha = 0.79 \pm 0.08$ for $M \geq 3.0$. At large time scales (above the crossover scale) the slope of all scaling curves is $\alpha < 0.5$ indicating anti-persistence. The value of the scaling exponent obtained using DFA-1 for large time scales is $\alpha = 0.325 \pm 0.01$ for $M \geq 2.8$, $\alpha = 0.39 \pm 0.01$ for $M \geq 3.0$, $\alpha = 0.47 \pm 0.01$ for $M \geq 3.2$, and $\alpha = 0.44 \pm 0.02$ for $M \geq 3.3$, while the value of the scaling exponent obtained using DFA-2 for large time scales is $\alpha = 0.25 \pm 0.01$ for $M \geq 2.8$, and $\alpha = 0.40 \pm 0.01$ for $M \geq 3.0$. For magnitudes $M \geq 3.2$ and $M \geq 3.3$ we do not observe a crossover in the DFA-2 scaling curves. Instead they may be fitted by a straight line with slopes $\alpha = 0.52 \pm 0.01$ for $M \geq 3.2$ and $\alpha = 0.62 \pm 0.01$ for $M \geq 3.3$ indicating close to random behavior or weak persistence. The corresponding slopes are presented by straight lines in the figure

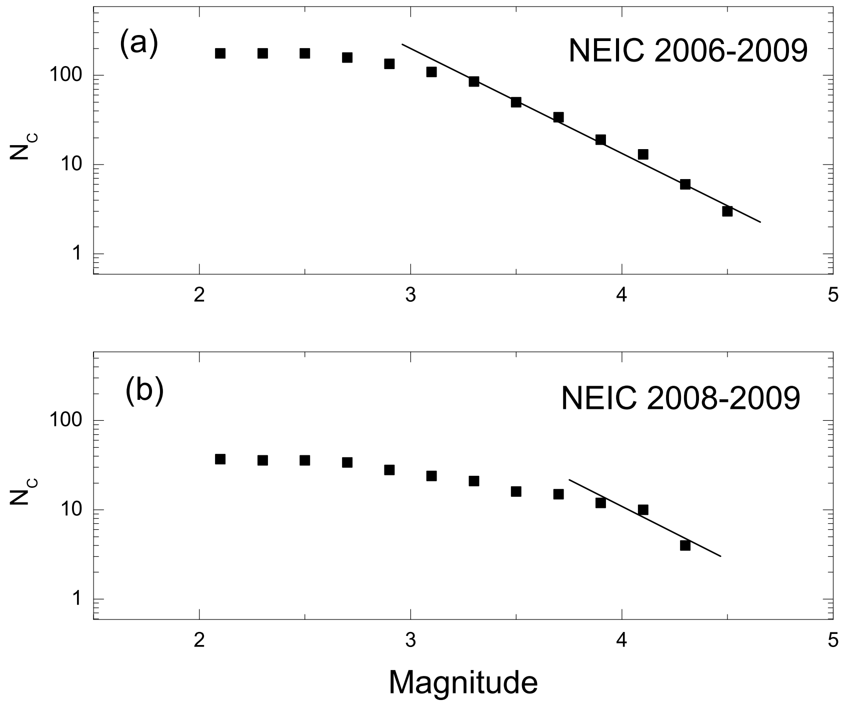

Fig. 11. Catalogue completeness: Gutenberg-Richter cumulative frequency – magnitude plot for the NEIC catalogue over the time periods (a) 2006-2009 and (b) 2008-2009. The plots deviate from linearity toward smaller magnitudes at $M_{TH} = 3.3$ for (a) and at $M_{TH} = 3.9$ for (b) indicating that the catalogue is complete above threshold magnitude $M_{TH} = 3.3$ over the time period 2006-2009 and above threshold magnitude $M_{TH} = 3.9$ over the time period 2008-2009

4. SUMMARY

We have analyzed long-term correlations in earthquake interoccurrence times derived from two earthquake catalogs related to the Bulgarian seismicity: (1) Bulgaria catalogue of earthquakes over the time period 1981-1990 (2) the catalogue of the USA National Earthquake Information Center (NEIC) for earthquakes after 1990. For both catalogs we have found evidence of long-term power-law correlations with scaling exponent $\alpha > 0.5$ indicating long-term memory and positive persistence. We also find that the scaling properties of the interoccurrence intervals are not temporally invariant but change with time. Specifically, for certain time periods we observe threshold magnitude dependence of the scaling exponent with tendency toward randomness for larger threshold magnitudes while for other time periods we do not observe significant change in the long-term correlation properties of the records over the range of threshold magnitudes from $M_{TH} = 2.8$ to $M_{TH} = 3.3$ or we even observe a slight increase of the persistence over the considered range of threshold magnitudes. Our finding of tendency toward randomness in the records with increase of the threshold magnitude is in agreement with the results of Lana et al. [2], Lennartz et al. [5], Telesca et al. [6]. We also note that this finding is based on longer segments of data than the segments for which we observe a slight increase in the scaling exponent α with the increase of the threshold magnitude or lack of threshold magnitude dependence which makes the latter less reliable. However, we note that similar results, i.e. increase of the scaling exponent with the increase of threshold magnitude, are obtained by Telesca et al. [7] for Central Italy seismicity. We also have demonstrated that systematic trends in the number of missed weak and moderate seismic events lead to a specific crossover behavior of the fluctuations of interoccurrence intervals.

Finally, we mention that this analysis is preliminary. Further more comprehensive analysis will clarify the details of spatio-temporal variability of long-term correlations in Bulgarian seismicity data.

Acknowledgements. We thank Ivan Dimov for useful help in computation.

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