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*Geophysics*

# Temporal and Spatial Variations of Scaling Behavior of Seismic Process in Caucasus

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**ABSTRACT. In the present research we investigate variation of scaling features of earthquakes' temporal and spatial distribution in Caucasus from 1960 to 2014. Data sets of waiting times and inter-earthquakes distances were obtained from the original and declustered Caucasus catalogues. For the assessment of long-range time-correlations of used data sets the method of Detrended Fluctuation Analysis (DFA) was used. We analyzed dynamical features of seismicity in Caucasus by assessing scaling characteristics of earthquakes' time and space distribution for shorter time periods and calculated DFA slopes for different sliding windows. Exactly, calculations were carried out for sliding windows of 500 data length. DFA scaling exponents variations of waiting time sequences obtained from the original and declustered catalogues were assessed by different order of polynomial fitting. In addition to fixed length data sets, the scaling exponents were separately calculated for 5 years long sliding windows. The data of surrogate waiting times obtained by shuffling of original series were processed also by DFA method. It was found that scaling exponents calculated for different windows vary in a wide range indicating variable temporal behavior from anti-persistent to persistent type. Different DFA scaling regimes are observed. Close to 0.5 and antipersistent scaling exponents were obtained for the time periods when the strongest regional earthquakes occurred. In the present work, we studied dependence of scaling properties of waiting times series and distances between consecutive earthquakes in the catalogue of Caucasus in different released energy range. We tested our results for scaling exponents calculated for different length of sliding windows.** *© 2015 Bull. Georg. Natl. Acad. Sci.*

***Key words:*** *seismology, catalogue, scaling, dynamics.*

For the last decade the interest to the investigation of scaling properties of seismic process increased and many different researches were carried out to study the dynamical features of earthquakes' spatial and temporal distributions [1-8]. According to the results of those researches, seismic process, in general, cannot be regarded as a random process in all its domains [7-11]. Moreover, it was even shown that

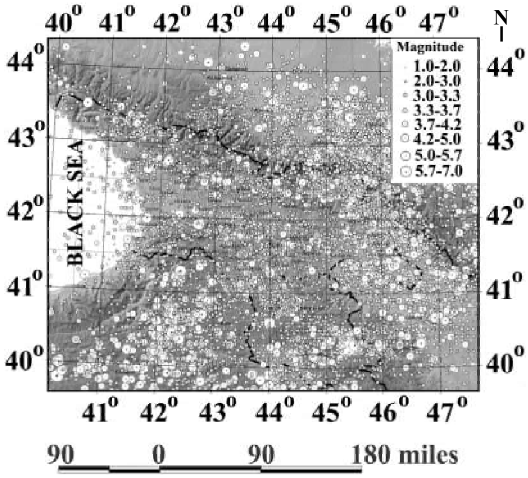


**Fig. 1.** Map of territory covered by the used Caucasian catalogue, 1960-2014.

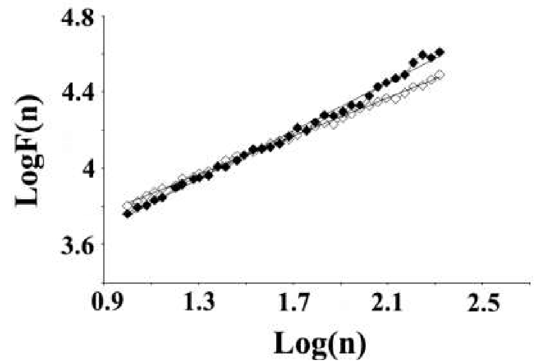


**Fig. 2.** DFA fluctuation curves of a) ITI sequences obtained from declustered, 1960-2014, Caucasian catalogue at M3.0 threshold (black squares – original data, white squares - phase randomized data). The order of the polynomial fitting is $p$=2. $n$ indicates the time scale (given here as the sequential number of data in the analyzed series). Linear fittings are shown by thin straight lines.

earthquakes' distribution in the temporal and spatial domains reveals features of close to low-dimensional, nonlinear structure [9].

Importance of such researches for Caucasus is obvious taking into consideration that Caucasus is seismically active zone and that in the last decades it was struck by strong earthquakes, such as Spitak 07.12.1988 (M6.9), Racha 21.04.1991 (M6.9), Racha 07.09.2009 (M6.1).

## Materials and Methods

We base our analysis on the data sets of waiting times, inter-earthquake distances and magnitudes obtained from the Caucasus earthquake catalogue (1960-2014) of M. Nodia Institute of Geophysics, Tbilisi State University and Institute of Earth Sciences, Ilia State University (Fig. 1).

Number of earthquakes in considered original Caucasus catalogue was 6684 ( $M \geq 3.0$ ). At the same time, the number of events in declustered, according to Reasenberg's algorithm (1985), catalogue was 4757 at $M \geq 3.0$ magnitude threshold.

For investigating the features of earthquakes' time distribution from these catalogues we calculated the time intervals (in minutes) elapsed between successive events at $t(i+1)$ and $t(i)$, named interevent time intervals, $\Delta t = t(i+1) - t(i)$ . Similarly, the inter-earthquake distances in km were calculated.

Long-range time-correlations in the investigated interevent time, distances and magnitudes data sets were assessed by the method of Detrended Fluctuation Analysis (DFA) [12, 13]. This method of analysis provides a quantitative parameter (DFA scaling exponent) and gives information about correlation properties of the analyzed data sets. In order to test the presence of dynamical structure in the used data sets we compared the results obtained on the original data sets with the results of data series obtained after shuffling the procedure.

According to DFA method, given time series of $N$ samples was integrated, then the integrated time series $Y(i)$ was divided into boxes of length $n$, and in each box the polynomial local trend $Y_n(i)$ of the order $p$ (p= 1,2,3...) was calculated and removed. Then $N/n$ mean squared residuals - Detrended Fluctuation Functions ($F(n)$), should be calculated for each box of size $n$:

$$F(n) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[Y(i) - Y_n(i)\right]^2}$$

Since $F(n)$ increases with the box size $n$, in case of fractal or self-similar properties of analyzed data, a power-law behavior $F(n) \sim n^{\alpha}$ can be revealed. It is important to note, that above mentioned process is repeated for different scales (box sizes) to obtain a power law behavior between $F(n)$ and $n$. If a power

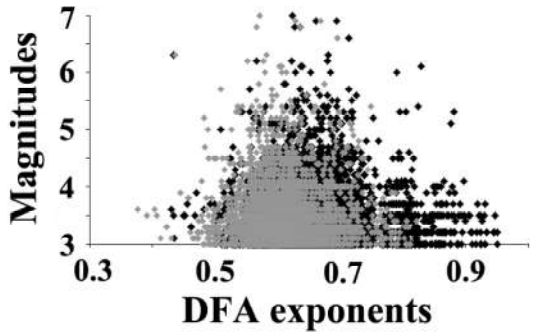


**Fig.3.** DFA scaling exponents variation of waiting times obtained from original (black), and declustered (grey) catalogues. Order of the polynomial fitting $p$=3.

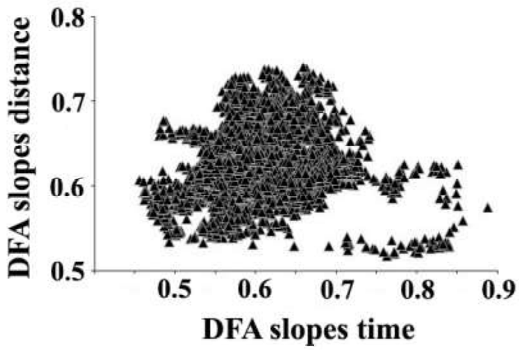


**Fig. 4.** DFA slopes of interevent times vs DFA scaling exponents of interevent distances sequences. Calculations for whole declustered catalogue for consecutive 500 data windows by 1 data step. Order of the polynomial fitting $p$=2.

law scaling exists, then $F(n)$ vs. $n$ relationship in a double logarithmic fluctuation plot will be linear or close to the linear and the scaling exponent $\alpha$ can be estimated. If scaling exponent $\alpha = 0.5$, we deal with the uncorrelated dynamics of random walk type [12, 13]. In this case the time series is identical to a white noise. It is known, that scaling exponent $\alpha$ gives information about the long-range power law correlation properties of the analyzed data sets. If $\alpha$ is different from 0.5, then the time series is regarded as a long-range correlated or anti-correlated. When $\alpha > 0.5$ the correlations in the signal are persistent or are antipersistent if $\alpha > 0.5$ [14, 15]. As it was mentioned the scaling exponent $\alpha$ is considered as an indicator of the nature of the fluctuations giving the information about the long-range power law correlation properties in the analyzed data sets. In case if the function $F(n)$ displays different power-law behaviors in double logarithmic plots of the DFA fluctuation function, one or more crossovers between different scaling regimes may be observed.

As an example of calculation in Fig. 2, we show results for original waiting times and its shuffled surrogates. We see clear differences in calculated scaling exponents values which was 0.6 for original sequence and 0.49 for the same sequence after shuffling. DFA can be accomplished for different order of the polynomial fitting in order to eliminate trends of certain origin. As we mentioned in previous section, these calculations were accomplished for sliding windows of different length.

## Results and Discussions

We started from the analysis of waiting times, inter-earthquake distances and magnitudes sequences obtained from the original and declustered Caucasus catalogues. This was an important part of research in order to understand how declustering procedure may affect long-range correlation features of earthquakes spatial, temporal and energy features. Further results of analysis for waiting times sequence is presented in Fig. 3. Here, for demonstration purposes the results for p=3 polynomial fitting is presented; for p=2 and p=4 the situation is practically the same.

As we see, earthquakes' temporal distribution remains mostly in a long-range correlation despite the fact that about 2000 events (aftershocks) were removed from the original catalogue by declustering procedure. In case of the other considered data sets situation was similar, i.e. aftershocks depletion by declustering procedure did not change the general dynamical features of analyzed process. Thus, in following we focused on the data sets from declustered Caucasus catalogue.

Next, in order to have understanding about relations between earthquakes time and space distribution we compared calculated scaling exponent val-

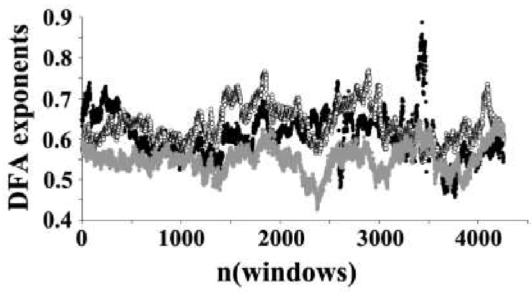


**Fig. 5.** DFA scaling exponents' variation for waiting times (black), distances (hollow), grey (magnitudes) data sets calculated for consecutive 500 data windows shifted by 1 data step. The order of the polynomial fitting $p$=2.

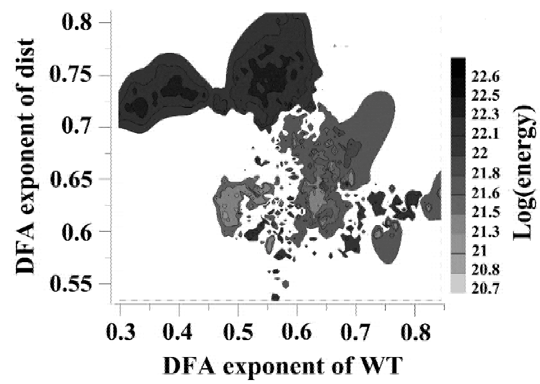


**Fig. 6.** DFA of inter-earthquake distances exponents vs. DFA exponent of waiting times (WT) calculated for consecutive 500 events windows. The seismic energy release (in Joule) is shown by shading – from grey to black (see the scale on the right insert).

ues. In Fig. 4 we present these DFA scaling exponents calculated for waiting times data sets versus scaling exponent values of inter-earthquakes distances sequences. We see that in most cases the earthquake space and time distribution reveals features of persistent long-term correlated process.

This is in good accordance with our earlier findings [10]. Analysis carried out on the data sets from declustered catalogues was important because very often more regular, close to low-dimensional part of seismic process is considered as a result of spatio-temporal correlations (clustering) of strong earthquakes with their aftershocks and foreshocks. We see here that after declustering there remains an essential part of events correlated in space and time.

General view of scaling exponents calculated for waiting times, inter-earthquake distances and magnitudes sequences accomplished for consecutive 500 data windows is presented in Fig. 5.

It is interesting that scaling exponents values vary in a wide range from window to window, which means that the long-range correlation features of seismic process undergo essential changes in different periods of observation.

Most important is that the extent of long-range correlation (scaling exponent values) reveal distinct relation to the amount of seismic energy release. Indeed, as we see in Fig. 6, in the periods of maximal seismic energy release, earthquake time distribution may reveal different behaviors ranging from anti-persistent and random-like to slightly persistent.

At the same time in a sense of spatial distribution we observe that the same time periods of maximal energy release are characterized by clearly persistent behavior.

In the time periods when the seismic energy release decreases by one or two units the earthquakes' time distribution becomes much more long-range correlated, contrary to the spatial distribution which looks less correlated than in periods with maximal seismic energy release.

## Conclusion

According to our results, the scaling exponents of waiting time and inter-earthquakes distances in the Caucasian seismic catalog calculated for consecutive sliding windows, show substantial variation through time of observation. Seismic process in the time and space domains generally reveals long-range correlations though in the time periods of strong earthquake occurrence anti-persistent and random-like behavior may take place.

*გეოფიზიკა*

# სეისმური პროცესის სკეილინგის მაჩვენებლების დროითი და სივრცული ვარიაციები კავკასიაში

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***ილიას სახელმწიფო უნივერსიტეტის დედამიწის შემსწავლელი მეცნიერებათა ინსტიტუტი, თბილისი, საქართველო*

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**ჩვენ მიერ წარმოდგენილ ნაშრომში გამოკვლეულია კავკასიის ტერიტორიაზე 1960-2014 წლებში მომხდარი მიწისძვრების განაწილების დროითი და სივრცული სკეილინგის თავისებურებანი. კვლევისათვის აუცილებელი მიწისძვრების მოლოდინის დროის და მათი დაშორების მანძილის მონაცემები მიღებულ იქნა ორიგინალური და დეკლასტიზირებული კავკასიის კატალოგიდან. მიწისძვრების მოლოდინის დროის, მათი დაშორების მანძილის და მაგნიტუდების გრძელპერიოდიანი დროის კორელაციები შეფასდა ტრენდმოცილებული ფლუქტუაციის ანალიზის მეთოდით (DFA). მიწისძვრებს შორის მანძილები და მოლოდინის დროები დათვლილ იქნა 500 მონაცემის სიგრძის ფანჯრებისათვის. DFA მეთოდის გამოყენებით დამუშავდა მოლოდინის სუროგატული დროის შერეული მონაცემები. ტრენდმოცილებული ფლუქტუაციის ექსპონენტები გამოთვლილ იქნა სხვადასხვა რიგის პოლინომებისათვის, როგორც ორიგინალური ასევე დეკლასტიზირებული კატალოგებისათვის. ტრენდმოცილებული ფლუქტუაციის ანალიზი განხორციელდა სხვადასხვა რიგის პოლინომებისათვის. ასევე დათვლილ იქნა 5 წლის მონაცემების სკეილინგის მაჩვენებლები. დადგინდა, რომ სხვადასხვა ფანჯრებად დაყოფილი მონაცემების სკეილინგური ექსპონენტები ვარირებენ ფართო დიაპაზონში ანტიპერსისტენტულიდან პერსისტენტულამდე. დაიკვირვებოდა ტრენდმოცილებული ფლუქტუაციის სკეილინგური მახასიათებლების ვარიაცია დროის სხვადასხვა პერიოდში. დაახლოებით 0,5 მნიშვნელობის და ანტიპერსისტენტული სკეილინგური ექსპონენტები მიღებულ იქნა რეგიონში ძლიერი მიწისძვრების მოხდენის პერიოდებისათვის. ნაშრომში კავკასიის მიწისძვრების კატალოგიდან აღებული მოლოდინის დროების და მიწისძვრებს შორის მანძილების სერიების სკეილინგურ მახასიათებლებს შორის დამოკიდებულება შევისწავლეთ გამოყოფილი სეისმური ენერგიის სხვადასხვა მნიშვნელობის დიაპაზონში. შემოწმდა სხვადასხვა სიგრძის ფანჯრებად დაყოფილი მონაცემების სკეილინგური ექსპონენტები.**

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