Tectonophysics 608 (2013) 857–865

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Analysis of temporal variation of earthquake occurrences in Caucasus from 1960 to 2011

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ARTICLE INFO

Article history:
Received 14 May 2013
Received in revised form 15 July 2013
Accepted 22 July 2013
Available online 2 August 2013

Keywords:
Seismicity
Dynamics
Temporal features of seismic process
Periodic components in earthquakes distribution

ABSTRACT

Frequency of earthquake occurrences in Caucasus is investigated on hourly and daily time scales. The observation period is 51 years, which is sufficiently long to perform a reliable statistics. Several methods (power spectrum, wavelet and Hilbert–Huang transformation) are applied to earthquake time series. Our findings show that earthquakes hourly and daily occurrence is not characterized by the dominant frequencies. However, many different oscillations with periods from hours to years and longer contribute to the frequency content of the earthquake time distribution, although their amplitude is rather low. The variation of the power of cyclic components in the temporal features of earthquakes occurrence is not uniform, but their amplification corresponds to the decrease of released local seismic energy.

1. Introduction

It is widely accepted that a detailed investigation of the structure of earthquake energy, space and time distribution is very important for earthquake hazard assessment as well as for understanding of fundamental properties of seismic processes (see e.g. Geller, 1997; Goltz, 1997; Kagan, 1997; Kiyashchenko et al., 2004; Matcharashvili et al., 2009; Rundle et al., 2000).

In particular, the analysis of the temporal features of earthquake occurrences on different time scales represents the focus of intense research. Several studies based on different conceptual frameworks are aiming at investigating earthquake temporal patterns using both field and laboratory data as well as numerical simulations (Ben-Zion and Lyakhovsky, 2002; Duma and Ruzhin, 2003; Issac et al., 2004; Lyakhovsky et al., 2001; Matcharashvili et al., 2000; Matcharashvili et al., 2000; Rundle et al., 2000; Shimshoni, 1971; Telesca et al., 2004a; etc). Most of such analyses agree that earthquake time dynamics is characterized by switching or intermittent behavior with periods of intense seismic activity interspersed with those of low seismicity (Ben-Zion and Lyakhovsky, 2002; Kiyashchenko et al., 2004; Lyakhovsky et al., 2001; Pliakis et al., 2012; Telesca et al., 2001; Vallianatos et al., 2012b). The details of such transition from one state (high seismic activity) to the other (low seismic activity) are still unclear. At the same time it is reasonable to presume that temporal variation of seismic processes should be caused by stress changes in the Earth's crust, which can be dynamically different and of both tectonic and non-tectonic origin (e.g. Agnew, 2007; Rundle et al., 2000). As a consequence, the question of earthquakes temporal distribution is still an open problem. Many authors emphasized the idea of random nature of seismic processes, which excludes the possibility of regular occurrence of earthquakes (e.g. Geller, 1997; Geller et al., 1997; Kagan, 1997; Parsons and Geist, 2012). At the same time, evidence of nonrandom features in earthquake generation in energy, space and time domains was shown in several papers (Goltz, 1997; liopoulos and Pavlos, 2010; Kiyashchenko et al., 2004; Matcharashvili et al., 2000; Pliakis et al., 2012; Rundle et al., 2000; Tzanis and Vallianatos, 2003; Vallianatos et al., 2012a).

Moreover, several studies claim the presence of cycles in earthquake temporal distribution (Berryman et al., 2012; Chen et al., 2012; Cochran et al., 2004; Kasahara, 2002; Tanaka et al., 2002). For example Metivier et al. (2009) reported clear correlation between the phases of the solid Earth tide and the timing of seismic events. These views, though controversial, are in principle consistent with the background tectonics comprising the complex processes of stress accumulation and stress release. In this respect it is important to note that the above mentioned non-tectonic forcings applied to the fault system, though substantially smaller than tectonic forces (few kPa-s vs. MPa-s (Iwata, 2012)), often are much more regular in time (e.g. lunar and solar tides, ocean waves, seasonal influences, etc. (Ide and Beroza, 2001; Iwata, 2012; Tanaka et al., 2002)), and thus could reasonably explain the evidence of cyclic components in earthquake occurrences. The ability of such small external influences to affect dynamical behavior of large systems is well known; modern concepts of

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http://dx.doi.org/10.1016/j.tecto.2013.07.033

complex systems, such as criticality and synchronization, provide a new scientific impulse for further theoretical developments of possible linking between earthquakes and different small external forcings (Chelidze et al., 2006; Peinke et al., 2006; Pikovsky et al., 2003; Rundle et al., 2000).

For example, recently was reported about correlation between aftershocks of the strong Christchurch (New Zealand) earthquake and solid daily tides, while no correlation with the mainshock was observed (Chen et al., 2012). Good correlation with tides and small shallow earthquakes was also often reported (see e.g. Cochran et al., 2004; Metivier et al., 2009; Tanaka et al., 2002).

In the present work, we do not intend to go further in the discussion about the presence of regular or irregular dynamical behaviors in earthquake generation. Instead, based on the observation, that earthquake temporal distribution is variable, we try to identify, whether the strength of the weak cyclic components in this process changes during analyzed period and whether there is any relationship between their possible change and characteristics of the level of background seismic activity (i.e. number of occurred earthquakes and released seismic energy). With this purpose we analyzed hourly and daily frequencies of earthquake occurrences in the 51-year long Caucasus seismic catalogue.

1.1. Data and methods of analysis

We investigated the process of earthquakes time distribution based on the Caucasian earthquake catalogue spanning from 1960 to 2011. Study area represents the segment of the Mediterranean Alpine Belt which is located between the still converging Eurasian and Africa-Arabian lithosphere plates and is a typical wide zone of continent–continent collision. Fig. 1 shows the distribution of earthquakes in the used catalogue, whose main characteristics already have been described in Telesca et al. (2012). Additionally here we shortly describe the type of network and entire catalogue.

From the beginning of 1960 in former USSR observation network created for Caucasus region was equipped by high sensitive analogue seismographs of different types. Mostly, among them were short period SKM type, long period SK and SKD. At that time data from adjacent territory of Turkey and Iran were available for the same type of network (thus we should expect spatial but not time rasterization of our data in Fig. 1). Later the number of seismic stations decreased. For example, in Georgia, instead of 40 stations in 1991, presently 25 digital seismic stations are operating, 9 of them are broadband type.

In Fig. 2, distribution of magnitude of completeness (Mc) versus observation time is presented. According to Fig. 2, the considered catalog for the threshold Mc = 3 is complete practically for whole analyzed period. It is important to mention that main results of our analysis below, stay the same for the time interval from 1960 to 2003, where Mc is of the order of 2.5 and where the later period with Mc very close to 3 is excluded.

In order to remove bias due to the presence of aftershocks, we declustered the catalogue using the Reasenberg's algorithm (1985) and selected only the events with magnitude $M \geq 3.0$

From this catalogue we calculated number of earthquakes occurred in consecutive hours and days of observational period and divided them by the total number of yearly occurred events; we name these data as frequencies of earthquake occurrences (FEO) (Fig. 3). The hourly and daily FEO series were then normalized to zero mean and unit variance.

Seismic energy has been calculated from the relation $\log_{10}E_s = 11.8 + 1.5M$ where M is magnitude (Kanamori, 1977).

To reveal hidden cyclic components in FEO data we used different methods. The well-known method of the power spectrum, based on the Fourier transform of the time series, indicates how the power of the series is concentrated at various frequency bands (Cohen, 1989; Gutierrez-Estrada and Pulido-Calvo, 2007; Park, 1998; Pasquini et al., 2006; Santos et al., 2010). However, nonlinear and nonstationary features that often characterize seismic processes could produce

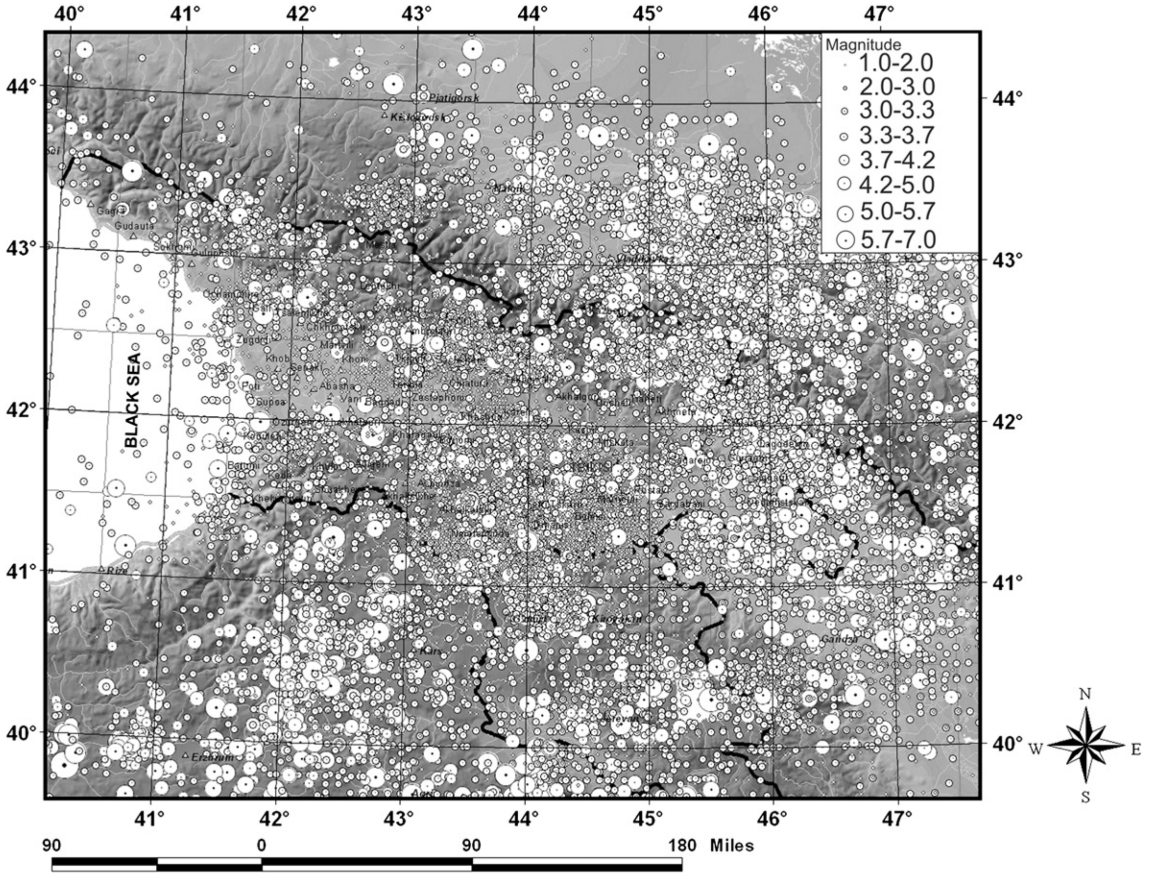

Fig. 1. Epicentral distribution of the earthquakes in Caucasus 1960–2011, declustered catalogue.

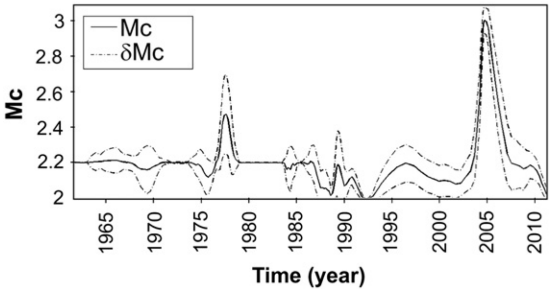

Fig. 2. Variation of magnitude of completeness (Mc) of declusterized Caucasian catalogue throughout observation time period.

misleading results and erroneous interpretations if based solely on the power spectrum (Cohen, 1989; Huang et al., 1998; Issac et al., 2004).

Much more efficient tool for our research is the wavelet analysis (Daubechies, 1990), used successfully for non-stationary time-series in different fields from geophysics to biology, economics, etc. The main difference between Fourier-based methods (i.e. power spectrum) and wavelets is that the last one enables a time–frequency representation of the series through decomposition, not based on sinusoidal functions. Wavelets use a so-called "mother function", from which "daughter" wavelets are obtained by means of a scaling procedure. Mother wavelet functions, localized in both frequency and time domains, slide along the time and contracts or stretches in the high- or low-frequency regions, respectively, allowing the identification of the dominant modes of variability and their variability through time. These characteristics permit a multi-resolution analysis of different data, including geophysical time series (Ashkenazy et al., 1998; Hloupis and Vallianatos, 2013; Kyriazis et al., 2006; Telesca et al., 2004b; Vallianatos and Hloupis, 2008).

The wavelet transform of a function $x(t)$ is defined as:

$$W(a,b) = a^{-\frac{1}{2}} \int_{-\infty}^{\infty} x\pi(t)h*((t-b)/a)dt$$

Where * indicates complex conjugate, a is the scale dilation parameter and b is the translation parameter; a and b physically stand for the inverses of the frequency and the time. $h(t)$ is the mother or analyzing wavelet. In the present work we used the Morlet wavelet as a mother wavelet. The spectral resolution in the wavelet transformation is achieved by selection of the wavelet size (or by dilating or contracting the chosen wavelet) and the temporal resolution follows from the location of the wavelet relative to the signal (Issac et al., 2004). We used continuous wavelet transformation (CWT) to calculate the power spectrum variation of the series on time and frequency. The CWT generates a two-dimensional (period/scale and time) wavelet space, on which the time series is represented (Issac et al., 2004). However, the CWT is limited by the Heisenberg's Principle of the time–frequency uncertainty relationship, according to which time and frequency cannot simultaneously be resolved with the same precision. Furthermore, the wavelet analysis entails the choice of the wavelet mother and that choice may not be optimal for the time-series being studied (Huang and Shen, 2005; Huang et al., 1998).

A further method that we used to perform our investigation of the FEO time series, is the Hilbert-Huang Transform (HHT) (Huang et al., 1998), which is a new approach to the analysis of non-stationary series, based on the use of an adaptive time–frequency decomposition that does not impose a fixed basis on the data, like in the CWT. Therefore, unlike the CWT, the HHT is not limited by the time–frequency uncertainty relationship. The HHT consists of two parts. In the first part, (the empirical mode decomposition—EMD) the series is decomposed into Implicit Mode Functions (IMFs), putting forward the scale characteristics imbedded in the signal (Huang and Wu, 2008); this is carried out by means of the sifting procedure that is ended according to a certain stop criterion (Huang and Shen, 2005) (see, e.g., Fig. 11, where the procedure is illustrated for one of the FEO time series). Each IMF represents a simple oscillatory mode which plays the role similar to a simple harmonic function for spectral analysis. At the same time IMF is much more general because it can have an amplitude and frequency varying with time, contrarily to the constant amplitude and frequency of a simple harmonic component (Huang and Wu, 2008). The second part is the Hilbert transformation of the IMFs, yielding the time–frequency representation (Hilbert spectrum) of each IMF.

Indicating as $x(t)$ a real signal and as $X_n(t)$ the IMFs, their Hilbert transform $H[X_n(t)]$ is

$$Y_n(t) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{X_n(\tau)}{t-\tau} d\tau,$$

where P is the operator called Cauchy principal value. The analytic signals, $Z_n(t)$ are given by $Z_n(t) = X_n(t) + iY_n(t)$, where i is the imaginary unit. From the analytic signals we can determine the instantaneous amplitude $A_n(t) = \sqrt{X_n(t)^2 + Y_n(t)^2}$ and phase $\varphi_n(t) = \arctan\left(\frac{Y_n(t)}{X_n(t)}\right)$. The instantaneous frequency is given by $f_n(t) = \frac{d\varphi_n}{dt}$. The total amplitude (or energy) from each frequency component is given by the marginal spectrum h_f, $h_f = \int_0^T A(f,t)dt$.

The HHT has already been applied in different scientific fields: fluid dynamics, ocean engineering, finance, system identification, medicine, seismology, etc. (see e.g. Battista et al., 2007; Ding et al., 2007; Huang and Shen, 2005; Rao and Hsu, 2008; Tang et al., 2007).

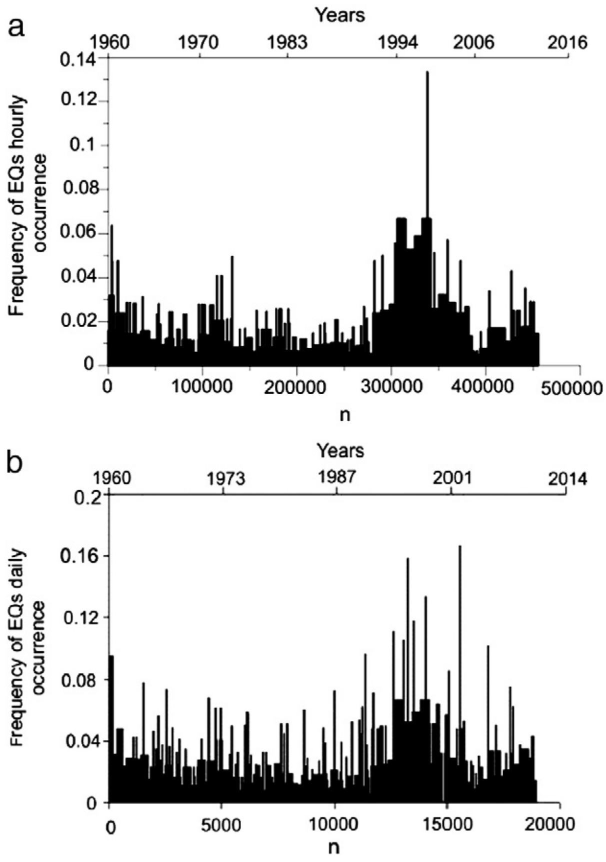

Fig. 3. Hourly (a) and daily (b) FEOs from the declustered Caucasian catalogue (1960–2011, M ≥ 3.0).

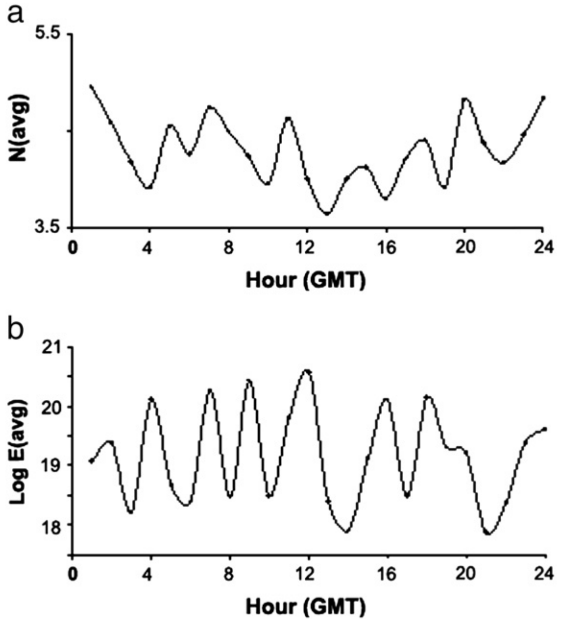

Fig. 4. Mean values of earthquakes (a) and released seismic energy (b) of M ≥ 3.0 earthquakes occurred hourly in Caucasus from 1960 to 2011.

1.2. Results of analysis

As a preliminary analysis, we calculated the hourly distribution of the average number of earthquakes occurred (Fig. 4a) and that of the average released energy (Fig. 4b) in a certain hour of the day, throughout considered time period from 1960 to 2011. Such analysis aiming to check if any significant change in the earthquake occurrence could be associated to a particular hour of the day was important because in earlier reports strong dependence of the probability of earthquake occurrence on the hour of day was claimed for several seismically active regions (Duma and Ruzhin, 2003; Duma and Vilardo, 1998; Shimshoni, 1971). From our results in Fig. 4, we see some variations in mean values of the number of earthquakes and the released seismic energy versus the hour of day, but they are not statistically significant. Thus for Caucasian region we can not confirm dependence of the number of earthquakes on the hour of day.

Next, taking into consideration that averaging procedure could distort and mask subtle features of the time dependent variations in seismic characteristics, we investigated the hourly and daily FEO time series, as described in the previous section, by means of the power spectrum method.

Fig. 5 shows the power spectral density of the daily FEO time series (similar characteristics are found for the hourly FEO time series, not shown here). The power spectrum of the original FEO series (Fig. 5a), does not reveal prevalent cyclic components in the analyzed data obtained from declustered Caucasian earthquake catalogue. It is flat in the higher frequency range, like the power spectrum of the shuffled FEO time series (Fig. 5b) and this is quite reasonable if we consider that a seismic process is very complex phenomenon and debate about its random character is still open (Geller et al., 1997; Kagan, 1997; Parsons and Geist, 2012). However, despite the broadness of the power spectrum of FEO time series, the presence of nonrandom features cannot be excluded, since a seismic process cannot be regarded as a purely random process (Goltz, 1997; Iliopoulos& Pavlos, 2010; Matcharashvili et al., 2000; Rundle et al., 2000).

Fig. 6 shows the CWT spectrogram for the original (Fig. 6a) and shuffled (Fig. 6b) daily FEO time series. It is evident that the shuffled time series shows a higher homogeneity in the temporal distribution of the frequency components with respect to the original data; in particular, the original FEO time series are characterized by a frequency spectrum more intense (darker areas in Fig. 6) from approximately 1990 to 2000 than in other periods.

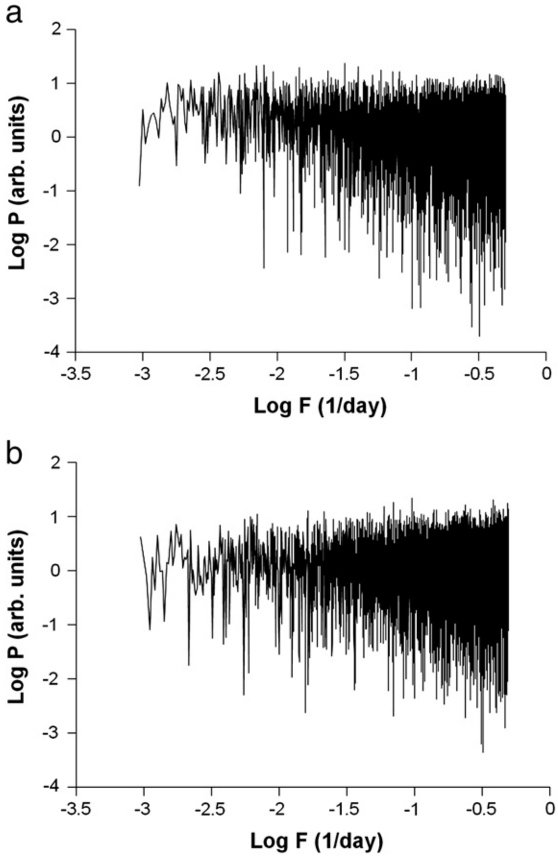

Fig. 5. Power spectrum of original (a) and shuffled (b) daily FEO time series from the declustered Caucasian catalogue 1960–2011, for events with M ≥ 3.0.

Fig. 7 presents the annual variation of the CWT power, which was calculated for one year time increments as an integral of the powers of cyclic components in the signal between specified frequencies. The CWT power for the hourly and daily FEO time series confirms conclusion, derived from analyzing the CWT spectrograms, namely, noticeable changes of the distribution of frequency components between approximately 1990 and 2000; furthermore, the comparison with the CWT power for the shuffled FEO time series corroborates proposition that such changes could not be purely random. In order to assess statistical significance of observed changes in distribution of cyclic constituents in FEO data for different time periods, we used *z_score* testing for original data and compilation of series of randomized data sets.

This often is a suitable way for correct evaluation of significance in statistical differences between two data sets when multiple realization of original data is impossible. Exactly, we generated 100 randomized data sets from each original hourly and daily FEO time series. CWT calculations have been performed for these randomized data series and mean wavelet coefficients have been calculated for each year (Kr_{avg}). *z_score* of the difference between wavelet coefficients of original time series (K_{orig}) and averaged values of Kr_{avg} is given by

$$z\_score = \left(\left|Kr_{avg} - K_{orig}\right|\right)/\sigma_r,$$

where σ_r is standard deviation of the set of randomized data series. For our calculations we took into consideration that distribution of cyclic components in considered time series has internal nonrandom structure if z is larger than threshold value z_t. Here we show results for *z_score*≥2.3, what corresponds to higher than 99% significance level in difference between Kr_{avg} and K_{orig} (Bevington and Robinson, 2002;

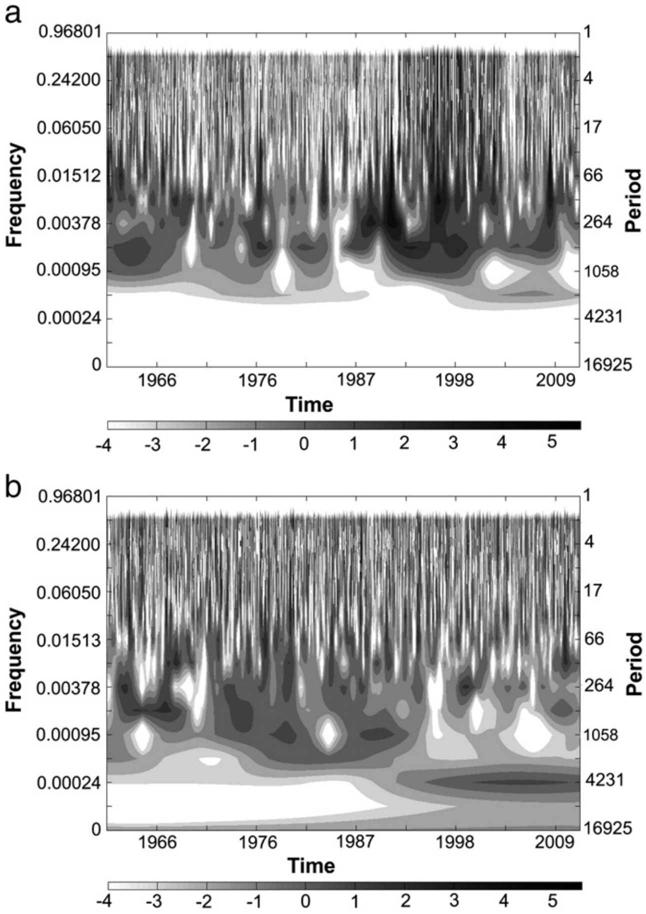

Fig. 6. CWT spectrogram of original (a) and shuffled (b) daily FEO data of filtered and normalized FEO series calculated for the whole available frequency range. Source—declustered Caucasian catalogue, 1960 to 2011.

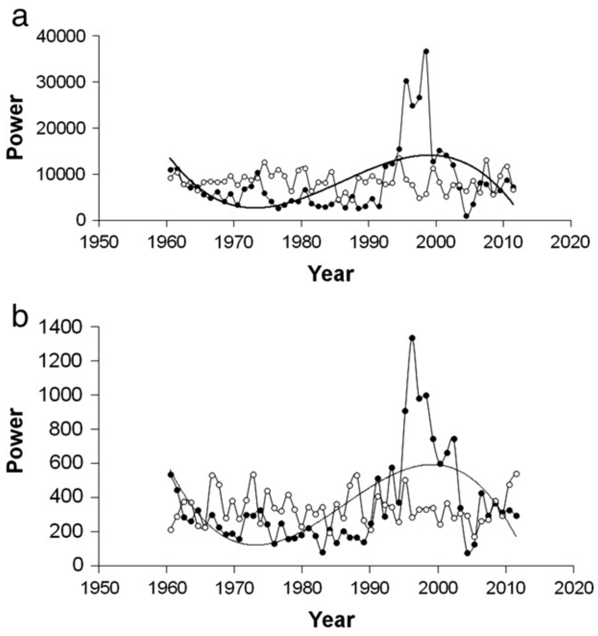

Fig. 7. Power of CWT spectrum vs. time relation of FEO time series obtained from declustered Caucasian catalogue, 1960–2011. a) hourly and b) daily time scales. Black and white circles correspond to original and shuffled data. For better visibility of occurred in original data changes, 3rd-order polynomial fit is shown by solid line.

Sales-Pardo et al., 2007). Results in Fig. 8 clearly indicate that at certain time periods in FEO time series spectral power of cyclic constituents significantly differ from the level, which can be regarded as occurred by chance.

Next, in order to assess the robustness of the obtained results against the influence of possible noise, we filtered our FEO time series by using two different de-noising techniques: 1) the Savitzky–Golay filter, and 2) the Singular Spectrum Analysis (SSA) decomposition (see Vautard et al., 1992, for the mathematical details).

The Savitzky–Golay smoothing filter is a low-pass filter, which approximates the data locally (corresponding to some user-chosen window) with an n^{th} degree polynomial, thus preserving up to the n^{th} moment of the data. Hence, it has the advantage over, for instance, a moving average filter, in preserving of values of local extremes (Press et al., 1997). The Savitzky–Golay smoothing filter has the characteristic to better retain the high-frequency content of the signal (Orfanidis, 2009). Fig. 9a shows the CWT power of the Savitzky–Golay filtered daily FEO signal. In Fig. 10a, is shown result of *z_score* calculation of significance of difference between Savitzky–Golay filtered original daily data and the set of its randomizations. From results in Fig. 9a, is evident that the main features of the CWT power are retained after used filtering procedure, what together with results in Fig. 10a, indicates that our results shown in Fig. 7, are robust.

The SSA approach, which is very helpful to investigate slowly varying oscillatory components buried in data sets of complicated and noisy signals Vautard et al. (1992), can be also used to remove the noisy components of a signal, retaining only those components that explain the most of variance. The original FEO time series were decomposed by using the SSA and reconstructed by adding the first 8–10 components explaining at least 50% variance of the original signal, thus removing

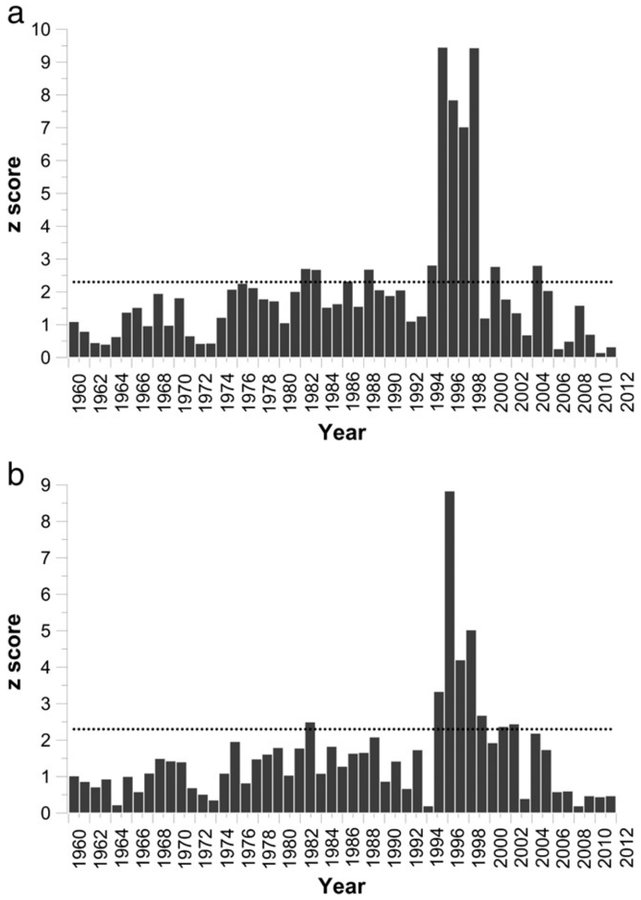

Fig. 8. Z_score values of difference between original time series and randomized data sets, a) hourly and b) daily time scales. Dotted line corresponds to 99% significance level.

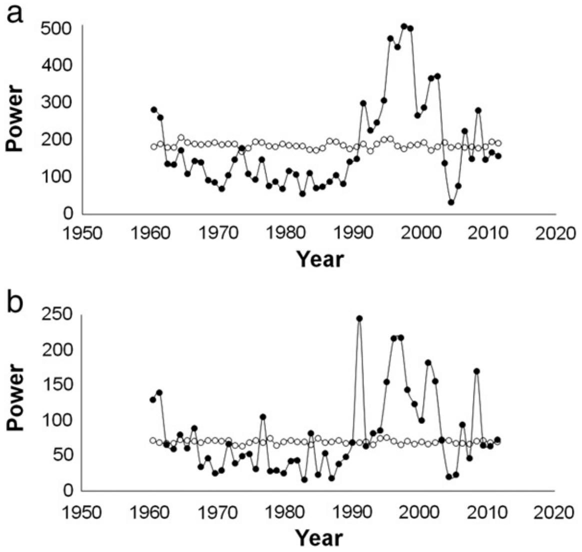

Fig. 9. Power of CWT spectrum vs. time relation of daily FEO time series obtained from declustered Caucasian catalogue, 1960–2011. a) smoothed by Savitcky–Golay filtering and b) reconstructed from the first 8 SSA components data sets. Black and white circles correspond to original and shuffled data. Solid line is the 3rd-order polynomial fit.

the noisy components. These reconstructed time series contain many different cycles with periods ranging from several hours to half year and more. Many of these cycles, which should indicate natural variations of different origin, have been subject of intense investigation concerning the possible influence of some forcings on the timing of earthquakes occurrence (Metivier et al., 2009). However, there are different arguments pro and contra about such timing of earthquake triggering (Kasahara, 2002; Metivier et al., 2009; Vidale et al., 1998, see also references therein).

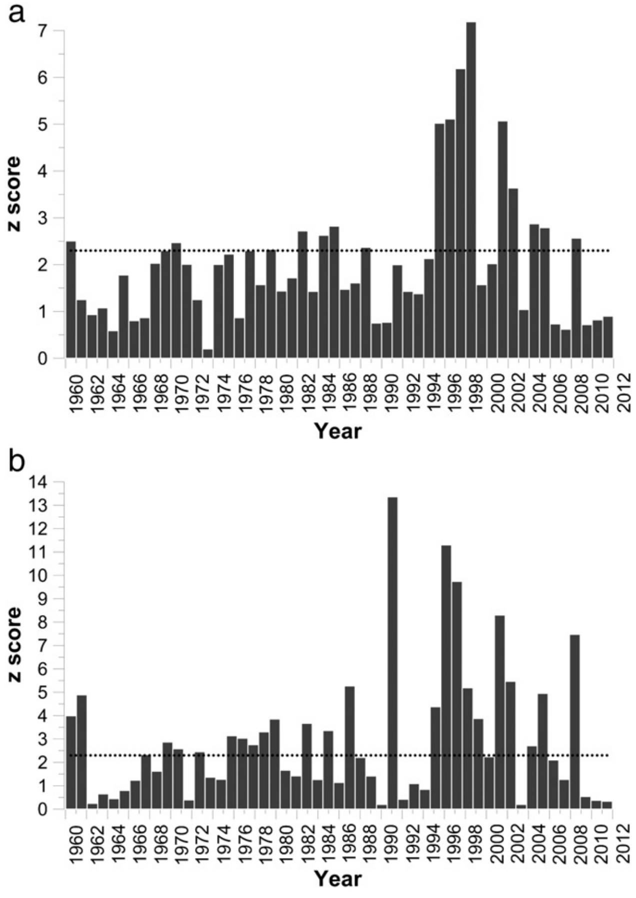

Fig. 10. Z_score values of difference between, a) Savitzky–Golay filtered original daily FEO time series and the set of their randomizations, b) SSA-reconstructed daily FEO time series and the set of their randomizations data sets. Dotted line corresponds to greater than 99% significance level.

Fig. 9b shows the annual CWT power of the SSA-reconstructed daily FEO time series and Fig. 10b presents result of *z_score* calculation of significance of differences between SSA-reconstructed data and the set of its randomizations. Similarly to the results shown in Fig. 9a and in Fig. 7 there is a clear evidence that the frequency content change between approximately 1990 and 2000 is not due to noise effects and that these changes are significant (see Fig. 10).

Results obtained for hourly FEO data subjected to Savitzky–Golay filtering as well as their SSA- reconstructions are similar to daily ones and are not shown here.

Next, we applied the HHT analysis of the hourly and daily FEO time series. Fig. 11 presents as an example of EMD the 15 IMF-s and the residual of the daily FEO time series. We can see that in all the IMFs, except the 13th and the 15th one, the highest amplitudes are observed in the period from about 12000 to 16000 days. The 13th IMF shows high amplitudes at the beginning of observed time interval at low frequency (about 0.00075 1/day). The 15th IMF is characterized by a frequency of approximately 0.00014 1/day with approximately constant amplitude. However, the amplitudes of 13th and 15th IMFs are low and they weakly contribute to the total energy of the original signal.

Therefore, we considered only the first 12 IMFs. We constructed the histograms of the frequency content of the 2nd up to the 12th IMF of the daily FEO time series in five consecutive segments of the whole observation period; such histograms are an estimation of the probability density function of the frequency content. Fig. 12 shows that the share of the low-frequency components is enhanced during the period from about 1990 to 2001. The dominance of the low-frequency range from about 0.01/day to 0.03/day is clearly shown in the 5th and 6th IMF (Fig. 13), and from day 11000 to day 15000 (i.e. approximately from 1990 to 2000). Therefore we further analyzed only this frequency range.

Since IMFs have good time–frequency resolution (see e.g. Huang and Shen, 2005; Huang and Wu, 2008), the Hilbert spectrum of the FEO time series should reveal high energy in those periods where the IMFs have high amplitude. Fig. 14 presents integral power derived from the Hilbert Transform of the 2nd up to the 12th IMF of the Caucasian daily FEO time series for the frequency range between 0.01/day and 0.03/day. Here the relationship of logarithm of the power vs. time actually represents the marginal spectrum, which is in good agreement with the results of the wavelet analysis of the daily Caucasian FEO data shown in Fig. 9. Significance of changes revealed by HHT analysis of daily FEO time series is assessed in Fig. 15.

The Hilbert power spectrum of the hourly FEO data shows similar to daily data increase of cyclic components for the time period from 1990 to 2000. In order not too overburden text, graphs of these results indicating changes in the frequency content of hourly FEO data from about 1990 to about 2000, are not presented here.

Fig. 16 shows the temporal variation of the number of earthquakes and that of the total seismic energy normalized to the yearly amount of events from 1960 to 2011. Comparing Fig. 16 with Figs. 7, 9 and 14 we can see that the enhancement of strength of same periodic components in the FEO data corresponds approximately to the decrease of the seismic activity, started in late 1980s and continued for about 15–20 years. Obviously, this long lasting decrease can not be related to the seismic quiescence prior to strongest recorded Caucasian earthquakes, Spitak and Racha, occurred in 1988 and 1991 respectively. Our guess is that territory of Caucasus during this 15–20-year long period can be considered as an area of stress shadow, where the tectonic stress was essentially released.

It seems also important to add here that the declustering procedure performed on the seismic catalogue does not lead to essential changes

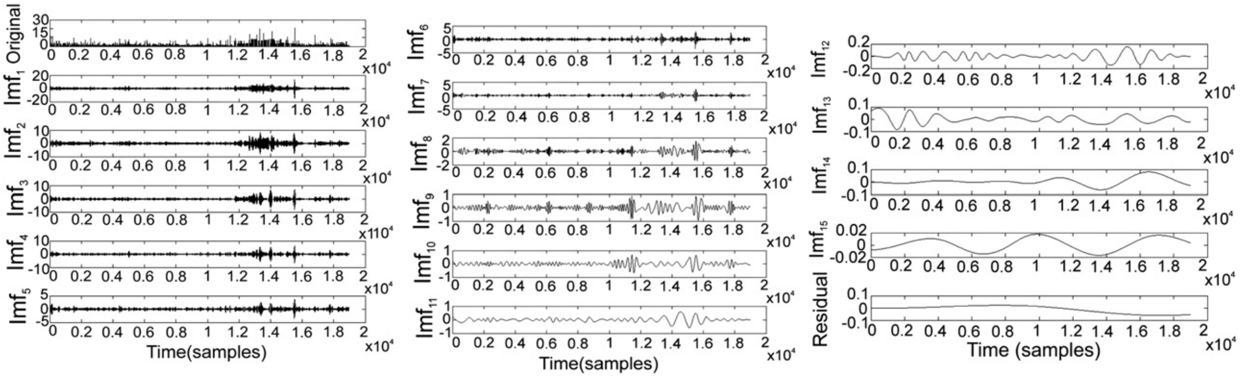

Fig. 11. Original daily FEO data (first row) and their EMD decomposition. Last row corresponds to residual.

in CWT power results. The time variation of the CWT power for the FEO time series derived both from the declustered catalogue and from the original one (not shown here) are very similar and this additionally indicates adequacy of used data as well as robustness of the methods applied.

2. Discussion

As it follows from results section WT and the HHT analysis shows that though the content of cyclic components in the frequency of earthquakes occurrence distribution in general is uniform, for some time periods the contribution of certain oscillatory modes may significantly increase.

In order to discuss such increase we should recall that the features of earthquakes temporal distribution are conditioned by the peculiarities of underlying stress changes of both tectonic as well as non-tectonic origins.

According to the present concepts, from a dynamical point of view the complicated process of tectonic stress change by its nature is nonrandom though high-dimensional. Therefore, it is difficult to assume that process of tectonic stress change itself may be a source of found enhanced strength of cyclic components in earthquake temporal distribution. On the other hand, factors that often are regarded as causing non-tectonic stress changes are much more regular—mostly quasi-periodic. For example, the tidal forces, one of the non-tectonic stress factors, consist of 505 to 27000 harmonics containing cycles from hours to years and longer (Agnew, 2007).

Among frequency components which amplification is documented in our results we indeed see well-known tidal constituents. For example, it is reasonable to link the dominance of the low-frequency components clustered around $f = 0.03$/day clearly shown in the 5th and 6th IMF (Fig. 13) to the long-term M_m (moon monthly) constituent with period 27.555 days (Agnew, 2007). The origin of components in the vicinity 0.01/day is not so obvious. We can only guess that this detail can be related to the effect of high-order synchronization connected with M_m period, namely periods of the order of 3 M_m (Chelidze et al., 2010). Besides, external impacts may not be only tidal triggering. According to Iwata (2012) tidal triggering is insufficient to determine the response of seismicity to oscillating stress changes, because the ranges of periodicities and amplitudes of stress oscillation due to earth tides are limited. Therefore, other close to quasi-periodicity stress influencing factors such as hydrological cycles, oceanic waves, atmospheric pressure, etc. should also be taken into consideration (here it should be stressed that not any stress influencing factors can be quasiperiodic by origin e.g. seismic waves arriving from remote large earthquakes (Iwata, 2012)).

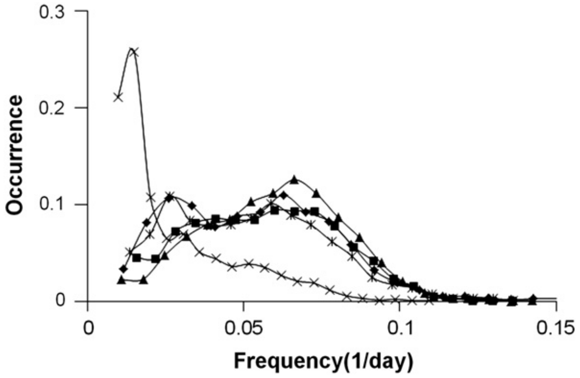

Fig. 12. PDF of frequency components of daily FEO for different periods of observation: diamonds-1960–1969, squares-1970–1979, triangles-1980–1989, circles-1990–2001, asterisks-2002–2011.

According to recent knowledge provided by the theory of complex systems, small external forces, when added at certain conditions, may essentially influence dynamical peculiarities of processes in a complex system (Chelidze and Matcharashvili, 2007; Meyers, 2009; Rundle et al., 2000; Strogatz, 2000). From this point of view at certain conditions small cyclic forcings may be regarded as a cause of essential changes occurring in the seismic process. Moreover such changes may trigger series of events, when a tectonic system is close to critical conditions. This was clearly demonstrated in laboratory experiments on triggered/synchronized stick-slip processes (Chelidze et al., 2006, 2010). It is obvious that changes in the seismic process caused by continuous weak external impacts may occur mainly at special stress/strain and periodicity conditions which do not always exist. Thus, all mentioned above, more or less quasi-periodic weak forces (weak compared to tectonic forces) in fact may cause an increase of the power of certain cyclic components in the time dynamics of the complex seismic process at certain systems conditions (Pikovsky et al., 2003; Strogatz, 2000).

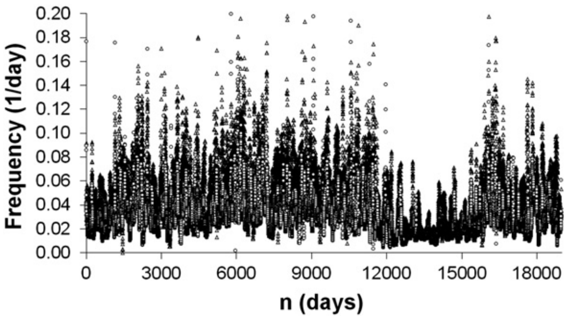

Fig. 13. Variation of frequency content of IMF 5 and IMF 6 in daily FEO throughout the observation period.

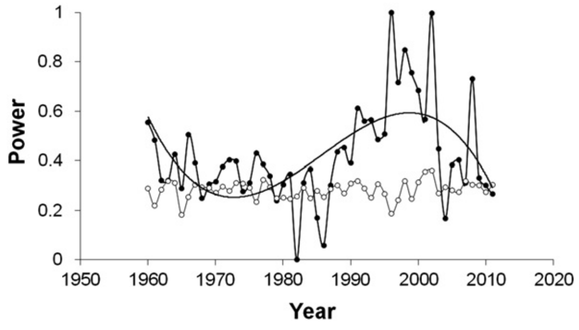

Fig. 14. Log Power vs. time relation of Hilbert Energy Spectrum of daily FEO time series. White circles correspond to Hilbert Energy Spectrum of shuffled data. Solid curve 3rd-order polynomial fit.

We found that conditions, when the increase of the power of cyclic components may occur (Figs. 7, 9, and 14) correspond to the decrease of the local seismic energy release (Fig. 16). This could be explained by the fact that increased seismic activity means more inter-correlated system; contrarily to this, during the decrease of seismic activity, the tectonic system could be less inter-correlated and thus closer to randomness. In this last case, unstable periodic orbits of the considered dynamical system can be easier trapped by different imposed external cycles that indeed strengthen certain cyclic components. Our earlier findings of fragment asperity interaction support conclusion about changed inter-correlations in tectonic system during different stages of seismic cycles. Indeed, from the nonextensive analysis of Caucasian earthquakes magnitude distribution it was concluded that during relatively quiet time periods (when earthquakes of small magnitude occur) the ordering within the system of fault fragments decreases (Matcharashvili et al., 2011). During these periods, when accumulated stress energy is supposedly released mostly through the relative movement of small fragments, the amount of accumulated stress is relatively small and thus correlated behavior of the whole system can not yet be initiated (Chelidze and Matcharashvili, 2007; Matcharashvili et al., 2011). At the same time, it is obvious that dynamics of a random and less correlated system makes possible for certain internal cycles to be easier trapped and amplified by external periodic influences; strength of some cyclic components in time evolution can be increased. Contrarily to this, when strong earthquakes are in preparation (like in 80th of last century in Caucasus) the system becomes much more correlated and the external cycles would not reveal their influence on local earthquakes time evolution.

In other words we assume that in the periods of released tectonic strain (stress shadow effect after strong earthquakes) increases, which promotes triggering and synchronization of seismic events by weak external forcing. This pattern is known in synchronization theory as Arnold's tongue phenomenon (Pikovsky et al., 2003). The Arnold's tongue effect has been confirmed in laboratory stick-slip experiments with superimposed periodic forcing (Chelidze et al., 2006), which means that the same phenomenon can be expected at the earthquake scale also.

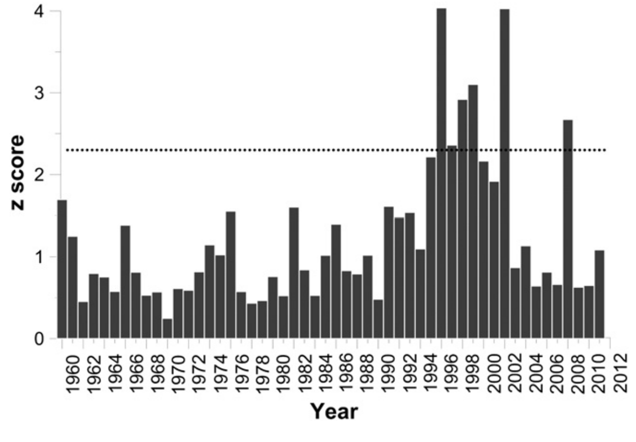

Fig. 15. Z_score values of difference between Hilbert power of daily FEO time series and the set of its randomizations data sets. Dotted line corresponds to 99% significance level.

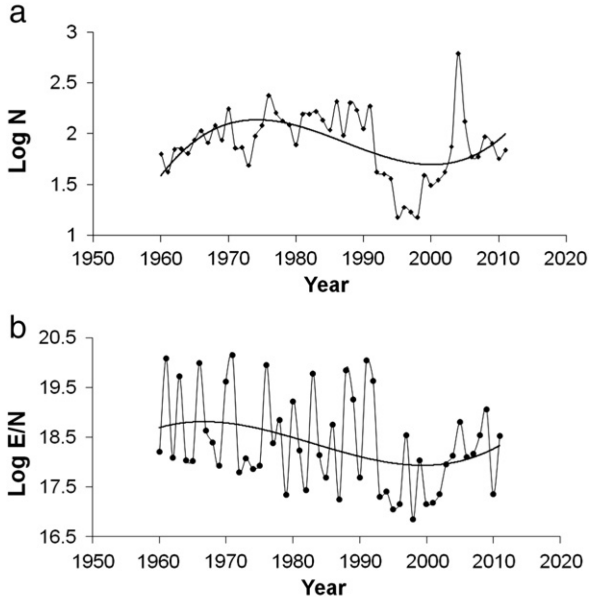

Fig. 16. a) Number of M > 3.0 earthquakes occurred yearly and b) released yearly seismic energy in Caucasus from 1960 to 2011 normalized to the yearly amount of earthquakes from declustered catalogue. Solid curve is the 3rd-order polynomial fit.

3. Conclusions

We investigated data on frequency of earthquakes occurrence in Caucasus from 1960 to 2011 at different time scales. Features of the frequency content of analyzed data as well as the time variability of their cyclic components were investigated by means of the WT and the HHT. It was shown that the time series of frequency of earthquake occurrence does not reveal presence of leading cycles. At the same time the temporal distribution of the power of weak cyclic oscillatory modes is not uniform and varies significantly during certain periods. Our analysis indicates that generally, the enhancement of different cyclic components coincides with the time periods of decrease in the amount of released local seismic energy.

Acknowledgment

The present study was supported by the 2012–2013 CNR-SRNSF Project “Investigation of large dam-induced changes in geophysical phenomena: the case of the Enguri Dam International Test Area (EDITA), Georgia”.

References

Agnew, D.C., 2007. Earth Tides. In: Herring, T.A. (Ed.), Treatise on Geophysics: Geodesy. Elsevier, New York, pp. 163–195.

Ashkenazy, Y., Lewkowicz, M., Levitan, J., Mølgaard, H., Thomsen, P.E.B., Særmark, K., 1998. Discrimination of the healthy and sick cardiac autonomic nervous system by a new wavelet analysis of heartbeat intervals. Fractals 6, 197–203.

Battista, B.M., Knapp, C.C., McGee, T., Goebel, V., 2007. Application of the empirical mode decomposition and Hilbert-Huang transform to seismic reflection data. Geophysics 72 (2), H29–H37.

Ben-Zion, Y., Lyakhovsky, V., 2002. Accelerated seismic release and related aspects of seismicity patterns on earthquake faults. Pure and Applied Geophysics 159, 2385–2412.

Berryman, K.R., Cochran, U.A., Clark, K.J., Biasi, G.P., Langridge, R.M., Villamor, P., 2012. Major earthquakes occur regularly on an isolated plate boundary fault. Science 336 (6089), 1690–1693.

Bevington, P., Robinson, D.K., 2002. Data Reduction and Error Analysis for the Physical Sciences. McGraw-Hill, N.Y.

Chelidze, T., Matcharashvili, T., 2007. Complexity of seismic process; measuring and applications — a review. Tectonophysics 431, 49–60.

Chelidze, T., Lursmanashvili, O., Matcharashvili, T., Devidze, M., 2006. Triggering and synchronization of stick slip: waiting times and frequency-energy distribution. Tectonophysics 424, 139–155.

Chelidze, T., Lursmanashvili, O., Matcharashvili, T., Varamashvili, N., Zhukova, N., Mepharidze, 2010. High-order synchronization of stick–slip process: experiments on spring–slider system. Nonlinear Dynamics 59 (1), 259–275.

Chen, L., Chen, J.G., Xu, Q.H., 2012. Correlations between solid tides and worldwide earthquakes since 1900. Natural Hazards and Earth System Sciences 12, 587–590.

Cochran, E.S., Vidale, J.E., Tanaka, S., 2004. Earth tides can trigger shallow thrust fault earthquakes. Science 306, 1164–1166.

Cohen, L., 1989. Time-frequency distributions: a review. Proceedings of the IEEE 77 (7), 941–979.

Daubechies, I., 1990. The wavelet transform, time-frequency localization and signal analysis. IEEE Transactions on Information Theory 36 (5), 961–1005.

Ding, H., Huang, Z., Song, Z., Yan, Y., 2007. Hilbert–Huang transform based signal analysis for the characterization of gas–liquid two phase flow. Flow Measurement and Instrumentation 18, 37–46.

Duma, G., Ruzhin, Y., 2003. Diurnal changes of earthquake activity and geomagnetic Sq-variations. Natural Hazards and Earth System Sciences 3, 171–177.

Duma, G., Vilardo, G., 1998. Seismicity cycles in the Mt. Vesuvius area and their relation to solar flux and the variations of the Earth's magnetic field. Physics and Chemistry of the Earth 23 (9–10), 927–931.

Geller, R.J., 1997. Earthquake prediction: a critical review. Geophysical Journal International 131 (3), 425–450.

Geller, R.J., Jackson, D.D., Kagan, Y.Y., Mulargia, F., 1997. Earthquakes cannot be predicted. Science 275 (5306), 1616–1625.

Goltz, C., 1997. Fractal and Chaotic Properties of Earthquakes. Lecture Notes in Earth Sciences, Berlin Springer.

Gutierrez-Estrada, J.C., Pulido-Calvo, I., 2007. Water temperature regimen analysis of intensive fishfarms associated with cooling effluents from power plants. Biosystems Engineering 96 (4), 581–591.

Hloupis, G., Vallianatos, F., 2013. Wavelet-based rapid estimation of earthquake magnitude oriented to early warning. IEEE Geoscience and Remote Sensing Letters 1, 43–48.

Huang, N., Shen, S., 2005. The Hilbert-Huang Transform and Its Applications. B & JO Enterprise, Singapore.

Huang, N., Wu, Z., 2008. A review on Hilbert-Huang transform: method and its applications to geophysical studies. Reviews of Geophysics 46 (RG2006), 1–23.

Huang, N.E., Shen, Z., Long, S.R., Wu, M.C., Shih, H.H., Zheng, Q., et al., 1998. The Empirical mode decomposition and the Hilbert spectrum for nonlinear and nonstationary time-series analysis. Proceedings of the Royal Society of London A 454, 903–995.

Ide, S., Beroza, G.C., 2001. Does apparent stress vary with earthquake size? Geophysical Research Letters 28, 3349–3352.

Iliopoulos, A.C., Pavlos, G.P., 2010. Global low dimensional seismic chaos in the hellenic region. International Journal of Bifurcation and Chaos 20 (7), 2071–2095.

Issac, M., Renuka, G., Venugopal, C., 2004. Wavelet analysis of long period oscillations in geomagnetic field over the magnetic equator. Journal of Atmospheric and Solar-Terrestrial Physics 66, 919–925.

Iwata, T., 2012. Earthquake triggering caused by the external oscillation of stress/strain changes. Community Online Resource for Statistical Seismicity Analysis. http://dx.doi.org/10.5078/corssa-65828518.

Kagan, Y.Y., 1997. Are earthquakes predictable? Geophysical Journal International 131 (3), 505–525.

Kanamori, H., 1977. The energy release in great earthquakes. Journal of Geophysical Research 82, 2981–2987.

Kasahara, J., 2002. Tides, earthquakes and volcanoes. Science 297, 348–349.

Kiyashchenko, D., Smirnova, N., Troyan, V., Saenger, E., Vallianatos, F., 2004. Seismic hazard precursory evolution: fractal and multifractal aspects. Physics and Chemistry of the Earth 29, 367–378.

Kyriazis, P., Anastasiadis, C., Triantis, D., Vallianatos, F., 2006. Wavelet analysis on pressure stimulated currents emitted by marble samples. Natural Hazards and Earth System Sciences 6, 889–894.

Lyakhovsky, V., Ben-zion, Y., Agnon, A., 2001. Earthquake cycle, fault zones, and seismicity patterns in a rheologically layered lithosphere. Journal of Geophysical Research 106, 4103–4120.

Matcharashvili, T., Chelidze, T., Javakhishvili, Z., 2000. Nonlinear analysis of magnitude and interevent time interval sequences for earthquakes of Caucasian region. Nonlinear Processes in Geophysics 7, 9–19.

Matcharashvili, T., Chelidze, T., Javakhishvili, Z., 2009. Dynamics, predictability and risk assessment of natural hazards. In: Fra Paleo, Urbano (Ed.), Building Safer Communities. Risk Governance, Spatial Planning and Responses to Natural Hazards. IOS Press, Amsterdam, pp. 148–161.

Matcharashvili, T., Chelidze, T., Javakhishvili, Z., Jorjiashvili, N., FraPaleo, U., 2011. Non-extensive statistical analysis of seismicity in the area of Javakhety, Georgia. Computers & Geosciences 37 (10), 1627–1632.

Metivier, L., Viron, O., Conrad, C.P., Renault, S., Diament, M., Patau, G., 2009. Evidence of earthquake triggering by the solid earth tides. Earth and Planetary Science Letters 278, 370–375.

Encyclopedia of Complexity and Systems Science. In: Meyers, R.A. (Ed.), Springer.

Orfanidis, S.J., 2009. Introduction to Signal Processing. Prentice Hall, Inc0-13-209172-0 (Previous).

Park, H.H., 1998. Analysis and prediction of walleye Pollock (Theragra chalcogramma) landings in Korea by time series analysis. Fisheries Research 38, 1–7.

Parsons, T., Geist, T.L., 2012. Were global M ≥ 8.3 earthquake time intervals random between 1900 and 2011. Bulletin of the Seismological Society of America 102 (4), 1583–1592.

Pasquini, A., Lecomte, K.L., Piovano, E.L., Depetris, P.J., 2006. Recent rainfall and runoff variability in central Argentina. Quaternary International 158, 127–139. http://dx.doi.org/10.1016/j.quaint.2006.05.021.

Peinke, J., Matcharashvili, T., Chelidze, T., Gogiashvili, J., Nawroth, A., Lursmanashvili, O., et al., 2006. Influence of periodic variations in water level on regional seismic activity around a large reservoir, field and laboratory model. Physics of the Earth and Planetary Interiors 156 (2), 130–142.

Pikovsky, A., Rosenblum, M.G., Kurth, J., 2003. Synchronization: Universal Concept in Nonlinear Science. Cambridge University Press.

Pliakis, D., Papakostas, T., Vallianatos, F., 2012. A first principles approach to understand the physics of precursory accelerating seismicity. Annals of Geophysics 55 (1). http://dx.doi.org/10.4401/ag-5363.

Press, W.H., Teukolsky, Saul A., Vetterling, William T., Flannery, Brian P., 1997. Numerical Recipes in C. The Art of Scientific Computing. Cambridge University Press.

Rao, R., Hsu, E.-C., 2008. Hilbert-Huang transform analysis of hydrological and environmental time series. Water Science and Technology Library 60.

Reasenberg, P., 1985. Second-order moment of central California seismicity, 1969-1982. Journal of Geophysical Research 90, 5479–5495.

Rundle, J., Turcotte, D., Klein, W., 2000. GeoComplexity and the Physics of Earthquakes. AGU, Washington.

Sales-Pardo, M., Guimer, R., Moreira, A.A., Nunes Amaral, L.A., 2007. Extracting the hierarchical organization of complex systems. Proceedings of the National Academy of Sciences of the United States of America 104 (39), 14224–15229.

Santos, J.F., Pulido-Calvo, I., Portela, M.M., 2010. Spatial and temporal variability of droughts in Portugal. Water Resources Research 46. http://dx.doi.org/10.1029/2009WR008071 (W03503).

Shimshoni, M., 1971. Evidence for higher seismic activity during the night. Geophysical Journal of the Royal Astronomical Society 24, 97–99.

Strogatz, S.H., 2000. Nonlinear Dynamics and Chaos. Perseus.

Tanaka, S., Ohtake, M., Sato, H., 2002. Evidence for tidal triggering of earthquakes as revealed from statistical analysis of global data. Journal of Geophysical Research 107.

Tang, J., Zou, Q., Tang, Y., Liu, B., Zhang, Xiao-kai, 2007. Hilbert-Huang Transform for ECG De-Noising. Bioinformatics and Biomedical Engineering 664–667.

Telesca, L., Cuomo, V., Lapenna, V., Macchiato, M., 2001. Intermittent-type temporal fluctuations in seismicity of the Irpinia (southern Italy) region. Geophysical Research Letters 28, 3765–3768.

Telesca, L., Lapenna, V., Macchiato, M., 2004a. Mono- and multi-fractal investigation of scaling properties in temporal patterns of seismic sequences. Chaos, Solitons & Fractals 19 (1), 1–5.

Telesca, L., Lapenna, V., Alexis, N., 2004b. Multiresolution wavelet analysis of earthquakes. Chaos, Solitons & Fractals 22, 741–748.

Telesca, L., Matcharashvili, T., Chelidze, T., 2012. Investigation of the temporal fluctuations of the 1960–2010 seismicity of Caucasus. Natural Hazards and Earth System Sciences 12, 1905–1909.

Tzanis, A., Vallianatos, F., 2003. Distributed power-law seismicity changes and crustal deformation in the EW Hellenic Arc. Natural Hazards and Earth Systems Sciences 3, 179–195.

Vallianatos, F., Hloupis, G., 2008. HVSR Technique Improvement Using Redundant Wavelet Transform, in Increasing Seismic Safety by Combining Engineering Technologies and Seismological Data, NATO Science for Peace and Security Series C: Environmental Security ISSN1874-6519. Springer Netherlands.

Vallianatos, F., Michas, G., Papadakis, G., Sammonds, P., 2012a. A non extensive statistical physics view to the spatiotemporal properties of the June 1995, Aigion earthquake (M6.2) aftershock sequence (West Corinth rift, Greece). Acta Geophysica 60 (3), 758–768.

Vallianatos, F., Benson, P., Meredith, P., Sammonds, P., 2012b. Experimental evidence of a non-extensive statistical physics behavior of fracture in triaxially deformed Etna basalt using acoustic emissions. Europhysics Letters 97, 58002.

Vautard, R., Yiou, P., Ghil, M., 1992. Singular-spectrum analysis: a toolkit for short, noisy chaotic signals. Physica D: Nonlinear Phenomena 58 (1–4), 95–126.

Vidale, J.E., Agnew, D.C., Johnston, M.J.S., Oppenheimer, D.H., 1998. Absence of earthquake correlation with Earth tides: an indication of high preseismic fault stress rate. Journal of Geophysical Research 103, 24567–24572.